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DETECTOR R&D at CALTECH
A Study in Scintillators, Fibres, Glues and Aging

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ABSTRACT

We have studied scintillators with different dimensions, scintillators extruded in different environment and scintillators made with different concentration of fluors. Our study has helped the MINOS collaboration in deciding the optimum dimension of the scintillator, optimum condition to produce the scintillator, and optimum concentration of fluors for the scintillators to give maximum light output. We have studied wavelength shifting fibres (WLS) from Bicron and Kuraray. We have studied WLS fibres with differnt wavelength shifter concentration and of different diameter, from Kuraray of Japan. Based on our study, at present the MINOS collaboration has decided to use Kuraray Y11(150), 1.2mm diameter fibre for the detector. We have also studied several glues. Based on our study the MINOS collaboration has decided to use EPON 815 C resin and TETA hardner, a two part glue for the baseline detector. We also report on the aging of scintillators, fibres, glues and the completed system for approximately the life time of the MINOS detector.

1 Introduction

The MINOS collaboration at its september 1997 collaboration meeting in Fermilab decided to use solid scintillator for the active medium of the calorimeter. The active detector planes will be made of extruded polystyrene scintillator strips, 10mm thick and 41mm wide. Each scintillator strip has a groove on the side for the wavelngth shifting fibre (WLS) and is co-extruded with an outer coating of TiO_2 for reflecting the light produced. The WLS fibres will be glued in the groove in each scintillator strip and will be read out at both the ends using a 16 channel Hamamatsu M16-R5900, photomultiplier tube.

At Caltech, we have been studying the characteristics, response and the light output using several kinds of scintillators produced by different vendors, fibres produced by Bicron and Kuraray, and of different glues to put the system together. We have studied different parameters which will help produce scintillator with highest light output, the response of the fibre for maximum light output and a good glue which could be trusted for long time. We are not only optimising the light output, but also looking at the cost effectiveness and the aging process of the system, to get the best overall cost-effective detector for the lifetime of the MINOS experiment.

1.1 Scintillator R&D

MINOS collaboration has decided to develope its own scintillator in consultation with experts from Fermilab. The scintillator could be developed either in two step process or in one step process. Both the processes are described below. As we will see, although the quality of the scintillator produced and the resulting light output, does not depend whether it is produced by one step or two step process, the cost for one step process is less by atleast 25% compared to two step process.

1.1.1 Two Step Process

In two step process[1], the first step involves mixing of polystyrene pellets, oil, primary and secondary fluors under high temperature environment and repelletisng them again. Then these pellets are again extruded in the form of scintillator strips of defined dimension. This process is very labour intensive because it almost repeats the whole process twice. Since these two steps are carried out at two different industries situated respectively in Illinois and Michigan, it becomes very time, manpower, and money intensive process.

The clear styron polystyrene called Dow-663 is procured from DOW plastics. It is mixed with DOW DC705 oil, PPO (primary scintillating fluor) and POPOP (secondary scintillating fluor) and the scintillator is produced at about 420^0F at Chroma Corporation. Chroma Corporation is located in McHenry county, IL, about 50 miles north of Fermilab. Chroma has a large physical plant, with many prodution lines in operation. Most are automated, but the one used for MINOS was staffed by one or two Chroma employees plus MINOS people. For most of the time during infusion process at least two MINOS people were working at Chroma.

Briefly, the process is as follows. Gaylords of Dow 663 polystyrene are shipped to Chroma at least a week ahead of time; a separate shipment of oil, PPO, and POPOP are sent to Chroma separately. These are unitized and measured at FNAL in advance. Liquid argon dewars are ordered and delivered to Chroma. Argon gas is used to purge the plastic bags in the gaylord boxes about 4 days before any other work is done. Purge flow is 20 scfh. At the time of infusion, one dewar is used to supply argon gas to the machine: one line (80 scfh) is inserted into the hopper and another line feeds a tented volume that surrounds the exit point of extruder (100 scfh). The machine screw is cleaned (to the metal) the day before the infusion process begins, as is the hopper.

As the infusiuon process begins, one of the gaylords is brought near the machine and the Dow 663 polystyrene pellets are hand-extracted (with a deep pail) and put into a metal cylinder nearby. The cylinder is filled with 100 lbs of Dow 663 polystyrene. A unitized volume of oil (136 gms of DC705) is added to the cylinder; a metal cover is taped to close the cylinder and it is moved a few feet to the mixing station. The cylinder is clamped into the mixer and the cylinder is shaken (tumbled) for 5 minutes. Then the cylinder is removed from the mixing station and PPO (460 gms PPO for every 100 lbs of polystyrene - 1% of polystyrene by weight), and POPOP (6.8 gms of POPOP for every 100 lbs of polystyrene - 0.015% of polystyrene by weight) are added, the lid is replaced and the cylinder is put back on the tumbling machine and it is again tumbled for 10 minutes.

After the contents have been mixed, the cylinder is placed near the machine's hopper. The cylinder lid is removed and about ten pounds of the mixture is removed with another pail and thrown into the hopper. One must be careful not to add much more material to the hopper because the pellets get stuck, requiring agitation with a polyethylene rod.

The mixture is blended in the machine, with temperatures between 410^0F and 420^0F, and extruded in the form of thick spaghetti. The exit point is covered with a tent that is vented with argon gas. Immediately after exiting the machine, the scintillator spaghetti (temperature about 390^0F as the scintillator spaghetti comes out of the machine) enters a water-cooling trough (temperature of scintillator spaghetti about 190^0F as it enters the trough which itself is at about 63^0F) and stays submerged for about one meter. There are five strands of spaghetti extruded simultaneously. The strands are lifted out of the water (by having to pass over large metallic "cookie sheets") and are drawn past a blow-drier (at room temp) into the pelletizer. At this point the average temperature of the scintillator is about 115^0F to 120^0F. Duration of water cooling is adjusted by moving the cookie sheets towards or away from the pelletizer, allowing for more or less water cooling. The pelletizer apparently cuts the spaghetti into short pellets, which are sorted in a sifting machine downstream of the pelletizer. The temperature of the pellets coming out of the pelletizer varies between 125^0F to 140^0F. About 83% of the initial polystyrene comes out as pellets certified "OK" by size, the other 15% are either too big or too fine. A very small fraction (nearly 2%) goes waste while the spagetti travels from the machine to the pelletizer. All pellets are kept, including the big and fine ones, which are sorted into separate buckets and kept seperately from the certified pellets. The average rate of infusion is about 100 lbs/hour. We produced nearly 6600 lbs of infused scintillator at Chroma in january of 1998. One batch was earlier produced in summer of 1997.

These infused plastics were sent to diffenent vendors for extrusion. The samples were sent to Kuraray, Quick Plastic and Polycast. They all produced the scintillators in the defined dimension, some coextruded with TiO_2 coating and some without it.

1.1.2 One Step Process

Quick plastic also produced TiO_2 coextruded scintillators where the DOW-663 polystyrene, PPO and POPOP were mixed together inline at their plant and the final product was produced. The separate mixing of polystyrene, PPO and POPOP and their pelletizing was done away with. One step process does not only saves time and money but a lot of effort and the quality of scintillator produced were not too different.

1.1.3 Different Batches of Scintillators

Following different batches of scintillators (41mm wide, 10mm thick with a groove on the side) have been produced and tested in last 18 months.

1. 1997 September Batch : Two Step Process at Chroma and Quick Plastics. PS + 1.0% PPO + 0.015% POPOP - Only one kind of scintillator was produced. The sample was coextruded with outer coating of 10% TiO_2.

2. 1998 March Batch : Two Step Process at Chroma and Quick Plastics. PS + 1.0% PPO + 0.015% POPOP - Several batches of scintillators were produced at Quick Plastic at different temperatures (350^0F, 375^0F and 400^0F) using Chroma premixed samples. Samples were also produced with different amount (10%, 12% and 15%) of TiO_2 coating and without TiO_2 coating. Samples were also produced in inert (Argon) environment.

3. 1998 March Batch : One Step Process at Quick Plastics only. PS+ 1.0% PPO + 0.015% POPOP - All components were mixed in hopper together. No oil was used. Temperature 400^0F. Polystyrene dried at 135^0F, 12% TiO_2 cap, no argon.

4. 1998 June Batch : Two Step Process at Chroma and Quick Plastics. PS + 1.0% PPO + 0.015% POPOP - Only one kind of scintillator was produced. Temperature 400^0F. Coextruded with 12% of TiO_2.

5. 1998 June Batch : One Step Process at Quick Plastics only. Eight kind of scintillators were produced at 400^0F and coextruded with 12% of TiO_2. Two different PPO concentration of 1.0% and 1.5% were used. For each of these PPO concentration four POPOP concentration of 0.010%, 0.015%, 0.030% and 0.045% were used respectively.

6. 1998 September Batch : One Step Process at Quick Plastics only. PS + 1% PPO + 0.030% POPOP - Only one kind of scintillator.

We have measured the relative light output and uniformity of these scintillators. The test setup consists of a 8m long dark box. The scintillators measured are either 70 cm in length or 8 meters in length. We have used both Bicron and Kuraray fibres for light transmission/collection. The phototube used is a Hamamatsu R5900-00-M16. The scintillators are placed in a dark box[2] and the fibre is optically coupled to the scintillator with uncured BC600 resin. We have used a Strongium 90 source which produces stopping beta. Measurements have been done with source directly above the fibre and also with source 5mm and 10mm transverse from the centre of the strip. The source can be moved along the length of the strip. Fibres used are 8 meters in length and if the scintillator is only 70 cm or one meter inlength, the measurement is done at a distance between 7 meters and 8 meters from the PMT, to regitser the response from the farthest end of a long strip and to allow the collected light to be attenuated. The fibre goes to the M16 where the DC current is integrated. For each kind of scintillator that we have tested, we have used atleast three pieces of that particular scintillator, and with each piece of scintillator we have used either two or three different fibres to make the measurement. This takes into account all possible systematics. Based on our measurement we have concluded that:

1. Among all the six batches of scintillator produced, the first batch of scintillator from september 1997 using two step process gives maximum amount of light. That particular batch of scintillator with 1.0% PPO and 0.015% of POPOP, coextruded with 10% outer cap of TiO_2 gives maximum amount of light, compared to any scintillator produced with any permutation/combination of parameters and material. Since it has not been possible to reproduce that scintillator, we would be better off comparing what other scintillators look like and how much light they give. This also suggests that it is very hard to reproduce the material as one would have naively thought. Based on our experience, as we will see from the different results, we must be ready to accept atleast $\pm 10\%$ variation in light output from different batches of scintillators.

2. The scintillator produced through inline mixing (one step process) at Quick plastic in march 1998 gave 15% to 25% extra light from the far end at a distance between seven and eight meters from the photomultiplier tube compared to the Chroma infused, Quick Plastic extruded two step scintillator. The light output comparison for one step and two step produced scintillator in march 1998 is shown in Figure 1. One possible reason for less light from two step process could be possible contamination of scintillator pellets at Chroma. As, I observed personally (BCC), that while the scintillator spaghetti was being pelletized at Chroma, sometimes the temperature of the pelletizer increased and it burned some of the spagetti. Although these blackened pieces were taken out carefully it was not possible to completely remove them. When clear extruded scintillator (no TiO_2 coating) with this batch of pelletized polystyrene and fluors was examined, one can see some black spots inside the extruded scintillator. That could be one of the possible reasons for less light output from this sample.

3. With 15% coating of TiO_2 on scintillator one gets about 10% extra light compared to 10% coating of TiO_2. But scintillator produced without any coating and covered with Tyvex, almost gave identical amount of light compared to scintillators with 10% TiO_2 coating. This is consistent with our earlier studies which suggested that Tyvex is a very good reflector of light (reflectivity is almost 95%). But for easy handling and uniformity we will use scintillators coextruded with TiO_2. The quality of TiO_2 coating has also seen to vary from one extrusion to another and it is our understanding that about 10% to 12% of TiO_2 coating is very good. If the amount of TiO_2 coating by weight/volume is increased, it will be at the cost of reduced amount of polystyrene and it may also affect the light output.

4. We also found that the scintillators produced at 350^0F were not very uniform and gave much less light compared to scintillators produced at higher temperature (400^0F). This

could be because at 350^0F the polystyrene did not melt properly and mixed uniformly. The light output for scintillators produced at 375^0F and 400^0F were almost identical.

5. As shown in figure 2, the chroma premixed sample (two step from march 1998) was found to be more uniform than the inline mixed sample at Quick plastic. The uniformity of all the scintillators produced are within $\pm15\%$ tolerance, defined for the detector.

6. We have also compared the light output when Argon was allowed to flow through the hopper and when it was not. In both cases the polystyrene was not purged with Argon for several days while it was sitting in the gaylord boxes. The light output in both cases are almost identical. This suggests that if Argon is used only briefly to purge the atmosphere while the scintillator is in hopper, it makes no difference.

At this stage, June 1998 batch of scintillators were produced with optimized parameter for scintillator production. In this batch all the samples were produced at 400^0F, coextruded with 12% of TiO_2. No Argon was used. The different samples produced are shown in table 1.

Light output for different samples were first studied with small pieces (70 cm in length) of scintillators. All measurements were made using several small pieces of scintillators of each kind, 8m long fibres at the far end from the PMT. At least two fibres were used with each scintillators. This permutation and combination of scintillator/fibre allowed for all possible systematic variation, due to different scintillators, fibres, human factors, fibre attachment to the PMT, fibre attachment to scintillator with glue etc. The light output for different scintillators are shown in table 2. The light output for different scintillators with varying amount of PPO and POPOP are compared with Sept 1997 QP scintillator. It is very clear that for one step process, the scintillator produced with 1.0% PPO and 0.030% POPOP gives maximum amount of light as compared to other combination of PPO and POPOP. Still, the light output for scintillator produced with this combination in june of 1998 is few percent less than the light output for scintillator produced with 1.0% PPO and 0.015% POPOP using two step process in september 1997. This reflects the problem involved in producing very consistent batch of scintillators.

Eight meter long pieces of scintillators with different PPO and POPOP combination were scanned with same fibre. As shown in figures 3, 4 and 5 respectively, it is very clear that scintillator produced in june 1998 using one step process with 1.0% PPO and 0.030% POPOP gives more light compared to one step scintillator with 1.0% PPO and 0.045% POPOP, scintillator with 1.0% PPO and 0.015% POPOP and scintillator with 1.5% PPO and 0.010% POPOP respectively. Based on this study it was decided to further produce scintillators only with 1.0% PPO and 0.030% POPOP.

In september of 1998, one more batch of scintillator was produced with 1% PPO and 0.030% POPOP, using one step process at Quick Plastic. As shown in table 2, the light output for this batch of scintillator is few percent less compared to scintillator produced with same combination of PPO and POPOP using one step process in june 1998. More details about this batch of scintillator is discussed further.

S.N	PROCESS	PPO (%)	POPOP (%)
1	TWO Step Process Chroma Premix & QP Extruded	1.0%	0.015%
2	ONE Step Process At QP Only	1.0%	0.010%
3			0.015%
4			0.030%
5			0.045%
6	ONE Step Process At QP Only	1.5%	0.010%
7			0.015%
8			0.030%
9			0.045%

Table 1: Different samples of scintillator produced in June 1998 with varying amount of PPO and POPOP, using one/two step process.

S.N	PROCESS	Scintillator Produced Month/Year	PPO(%)	POPOP (%)	LIGHT OUTPUT Range
1	TWO Step	June 1998	1.0%	0.015%	0.77-0.83
2	ONE Step	June 1998		0.010%	0.82-0.84
3				0.015%	0.85-0.90
4				0.030%	0.93-0.97
5				0.045%	0.89-0.91
6	ONE Step	June 1998	1.5%	0.010%	0.86-0.90
7				0.015%	0.83-0.90
8				0.030%	≈0.60
9				0.045%	≈0.60
10	TWO Step	Sept 1997	1.0%	0.015%	**1.00**
11	ONE Step	Sept 1998	1.0%	0.030%	0.90

Table 2: Light output compared for scintillators produced at different time with different concentration of PPO and POPOP. LIGHT OUTPUT compares light output for different scintillators produced at different time and with different fluor combination as compared to Sept 1997 TWO Step sample.

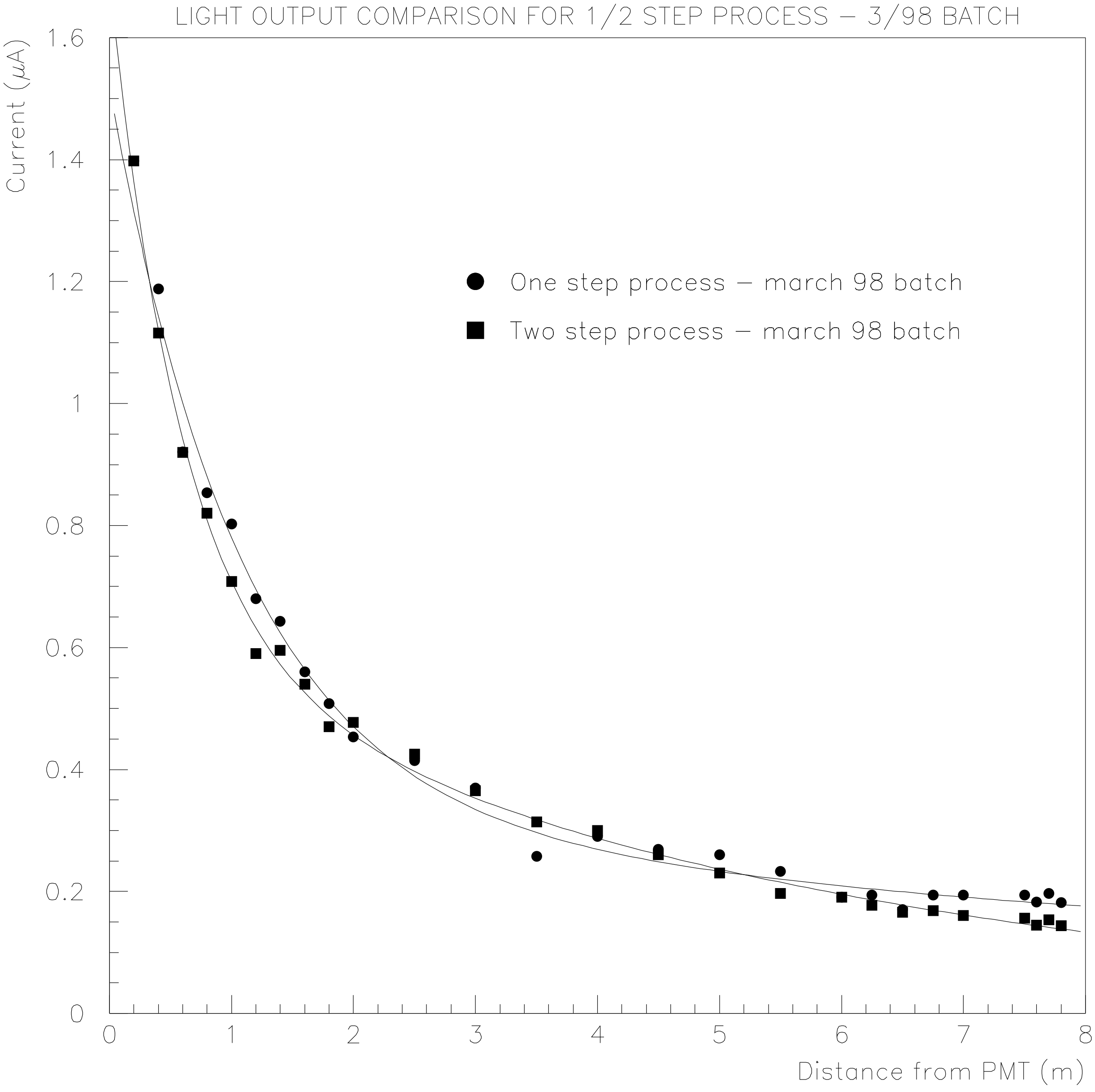

Figure 1: Light output comparison as a function of distance from the photomultiplier tube for Quick Plastic infused one step (inline) scintillator and Chroma pelletized, Quick plastic extruded, two step scintillator. The Y-axis has an arbitrary multiplicative factor of 10.

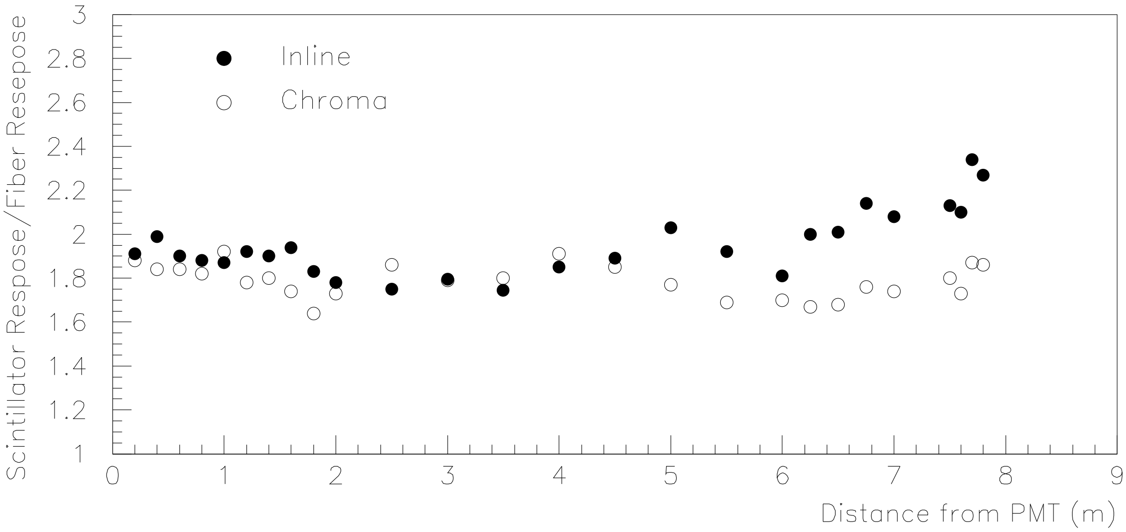

Figure 2: Uniformity of the scintillator given as scintillator response divided by fibre response as a function of distance from the PMT. The inline infused scintillator shown in dark circles are less uniform at the far distance.

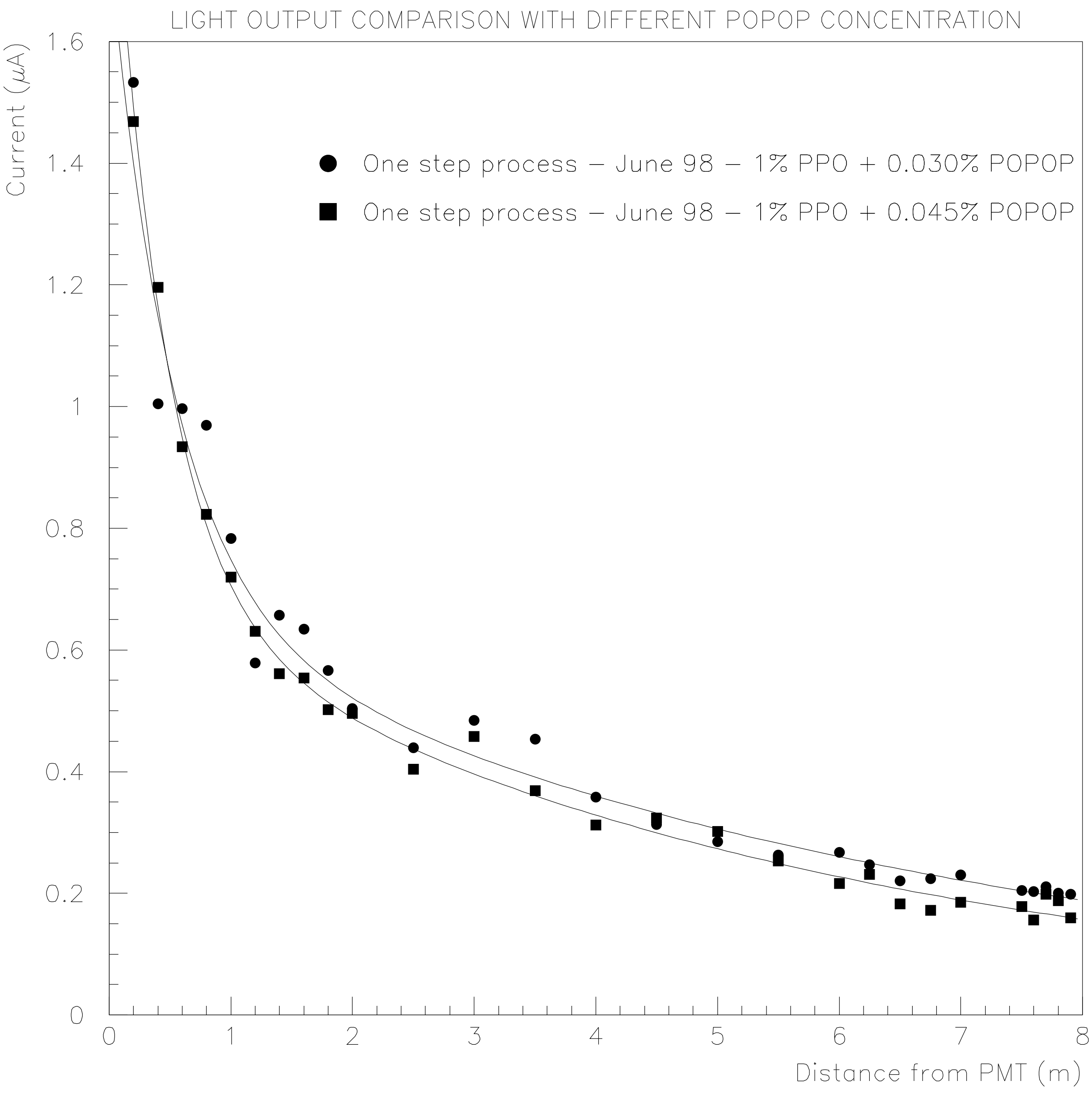

Figure 3: Light output comparison as a function of distance from the PMT for eight meter long scintillators pieces produced with 1% PPO with 0.030% POPOP, and 1% PPO with 0.045% POPOP respectively. For most of the length of the scintillator piece, scintillator with 0.030% POPOP gives about 10% more light compared to scintillator with 0.045% POPOP for the same PPO concentration. The Y-axis has an arbitrary multiplicative factor of 10.

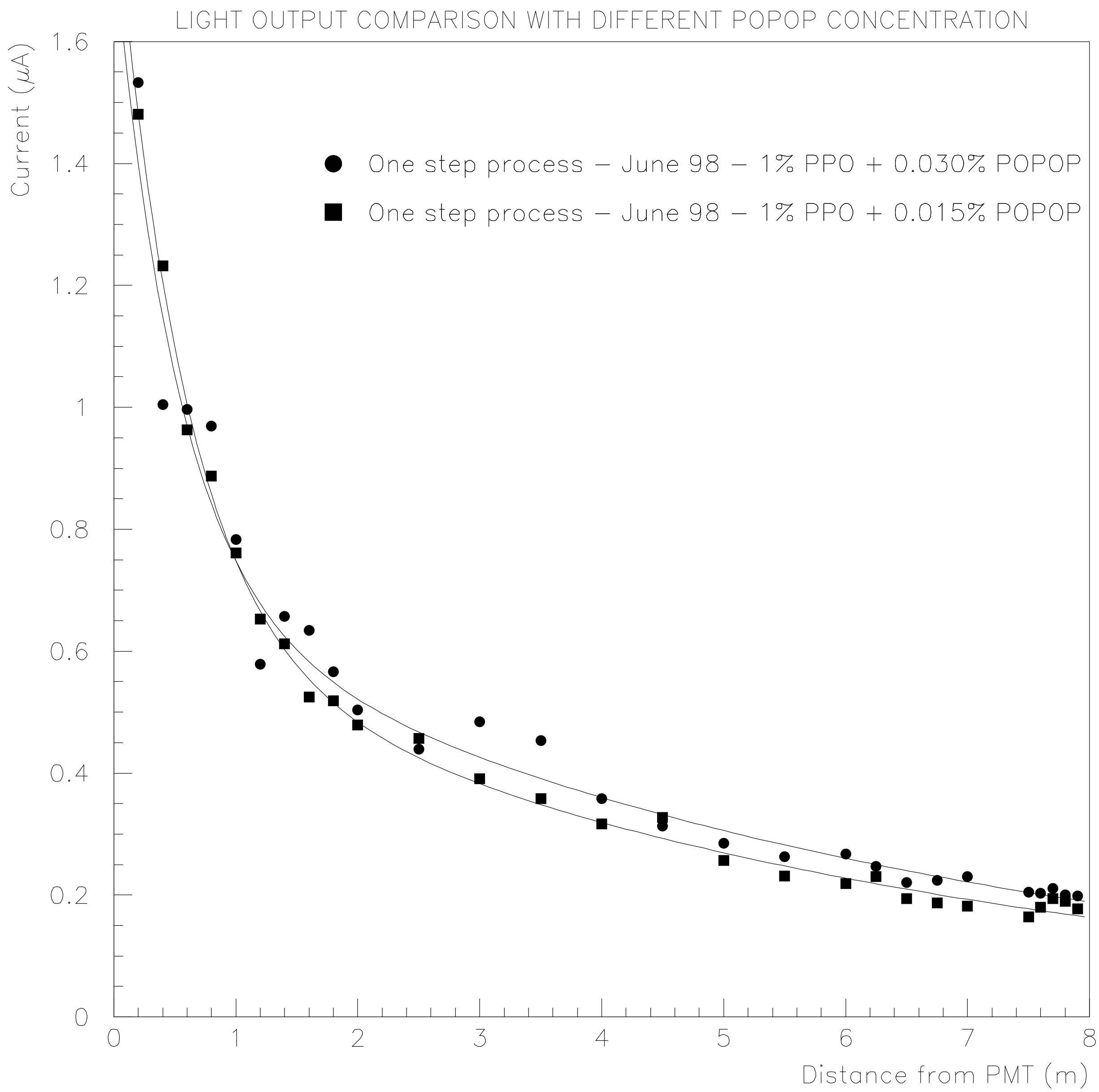

Figure 4: Light output comparison as a function of distance from the PMT for eight meter long scintillator pieces produced with 1% PPO with 0.030% POPOP, and 1% PPO with 0.015% POPOP respectively. For most of the length of the scintillator pieces, scintillator with 0.030% POPOP gives about 10% more light compared to scintillator with 0.015% POPOP for the same PPO concentration. The Y-axis has an arbitrary multiplicative factor of 10.

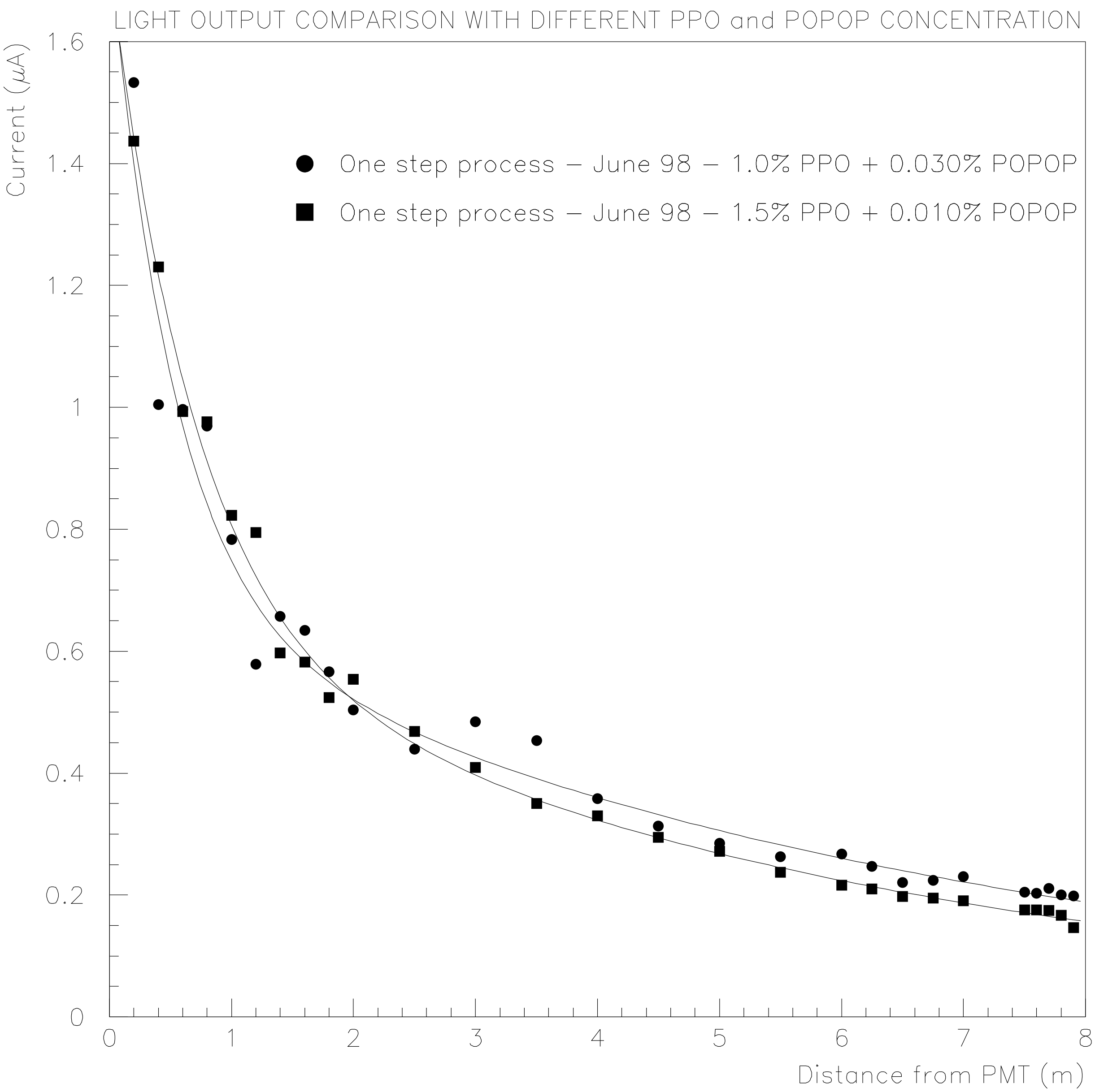

Figure 5: Light output comparison as a function of distance from the PMT for eight meter long scintillator pieces produced with 1% PPO with 0.030% POPOP, and 1.5% PPO with 0.010% POPOP respectively. For most of the length of the scintillator pieces, scintillator with 1% PPO and 0.030% POPOP gives about 10% more light compared to scintillator with 1.5% PPO and 0.010% POPOP concentration. The Y-axis has an arbitrary multiplicative factor of 10.

1.1.4 Uniformity of Scintillator from different batches, Effect on Light Output due to Quality of Groove and Some more thoughts

Very recently (in October 98), we again looked at the uniformity of light output from different pieces of scintillators from different batches. Figure 6, shows the light output for two pieces of 8m long Chroma/QP scintillator from september 97 batch, measured with the same fibre in identical condition. As we see, the data points for the light output measurement from these two pieces almost overlap with each other. This batch of scintillator was not only very uniform but had very good grooves and it gets reflected from the consistency of measurements. Figure 7, shows the same plot on the logarithmic scale. The variation between these two pieces are almost negligible. Since we had only two piece of 8meters long scintillator left from that batch, we could not measure any more. But figures 6 and 7 gives the idea how a good batch of scintillator should look like.

Figure 8, shows the light output from four pieces of 8meters long scintillator developed at QP in september 1998 using 1% PPO with 0.030% POPOP. Two of the pieces, number 1 and 2, have been measured with two fibres. We see that the variation among different pieces are really very large. The variation due to different fibre for any piece of scintillator is very minimal as is clear from overlap of data represented by open and close triangles for scintillator piece 2. Although, the scintillator number one, for which data has been shown in open and close square had narrow grooves, the variation due to two fibre is very small but this particular piece produces less light compared to others because the groove was not only narrow but also shallow. We also see that the light output (data points shown by dark stars) for scintillator piece 3 suddenly goes down at a distance of 6 meters from PMT. We looked at the scintillator and found that it had bad spots from 6meters to 8 meters. Thus we see that for this particular batch of scintillator, the uniformity was not very good because we did see bad spots, we found grooves which were narrow and shallow. Figure 9, shows the light output comparison for Chroma/QP 9/97 batch and QP 9/98 batch scintillator. This particular batch of scintillator (QP, 9/98 batch) will be not acceptable for detector development and one has to improve the quality of scintillator.

It is our understanding that for uniform light output the polystyrene, PPO and POPOP should be mixed very uniformly. The scintillator should be produced at some nominal temperature, so that it does not form lumps. Also the quality of the groove should be good enough that the fibre fits very well. The groove should not have only proper depth but also proper width for the fibre to fit properly. If the groove is deep enough but not wide enough, or wide enough but not deep enough, the fibre will be jutting out of the scintillator and will not be able to capture all the light. The groove should also not be very deep and wide so that the fibre completely gets into the scintillator and the light produced from the top portion of the scintillator is not captured. One has to very carefully study the quality, width and depth of the groove, for optimum light collection.

1.1.5 QP 1997 September vs RDN 1997 September Batch Scintillators

We have also studied scintillators with different transverse granularity. With Chroma infused pellets, scintillators were produced at Quick Plastic (QP) and RDN. QP produced scintillator was 10mm thick, 41mm wide and co-extruded with 10% of TiO_2, with a groove on one side in which WLS fibre could be glued. Scintillator produced at RDN company was 10mm thick,

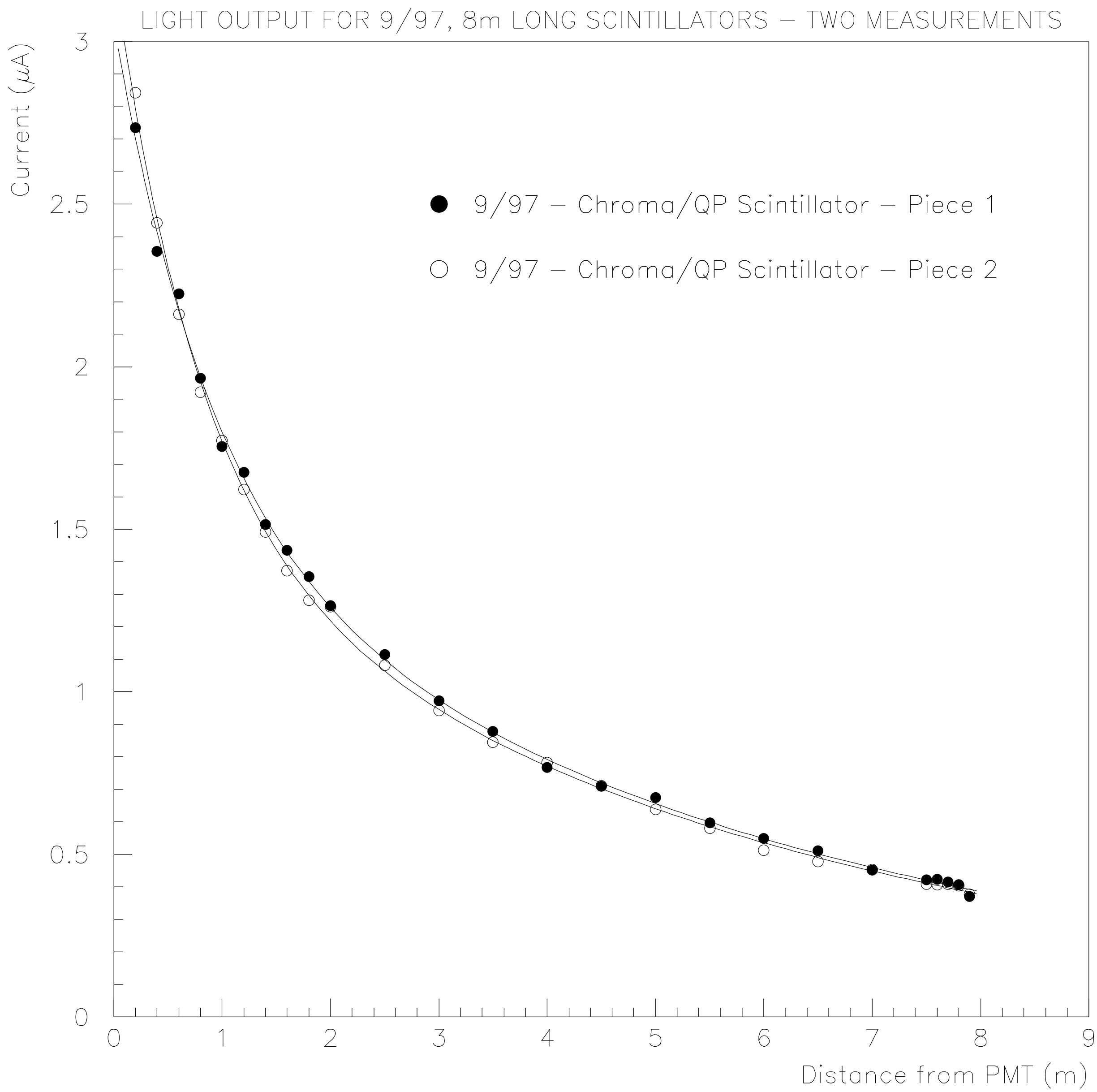

Figure 6: Light output comparison as a function of distance from the PMT for two pieces of eight meter long Chroma/QP scintillator produced in September 1997. The consistency of the result shows the uniformity of the produced scintillator. The Y-axis has an arbitrary multiplicative factor of 10.

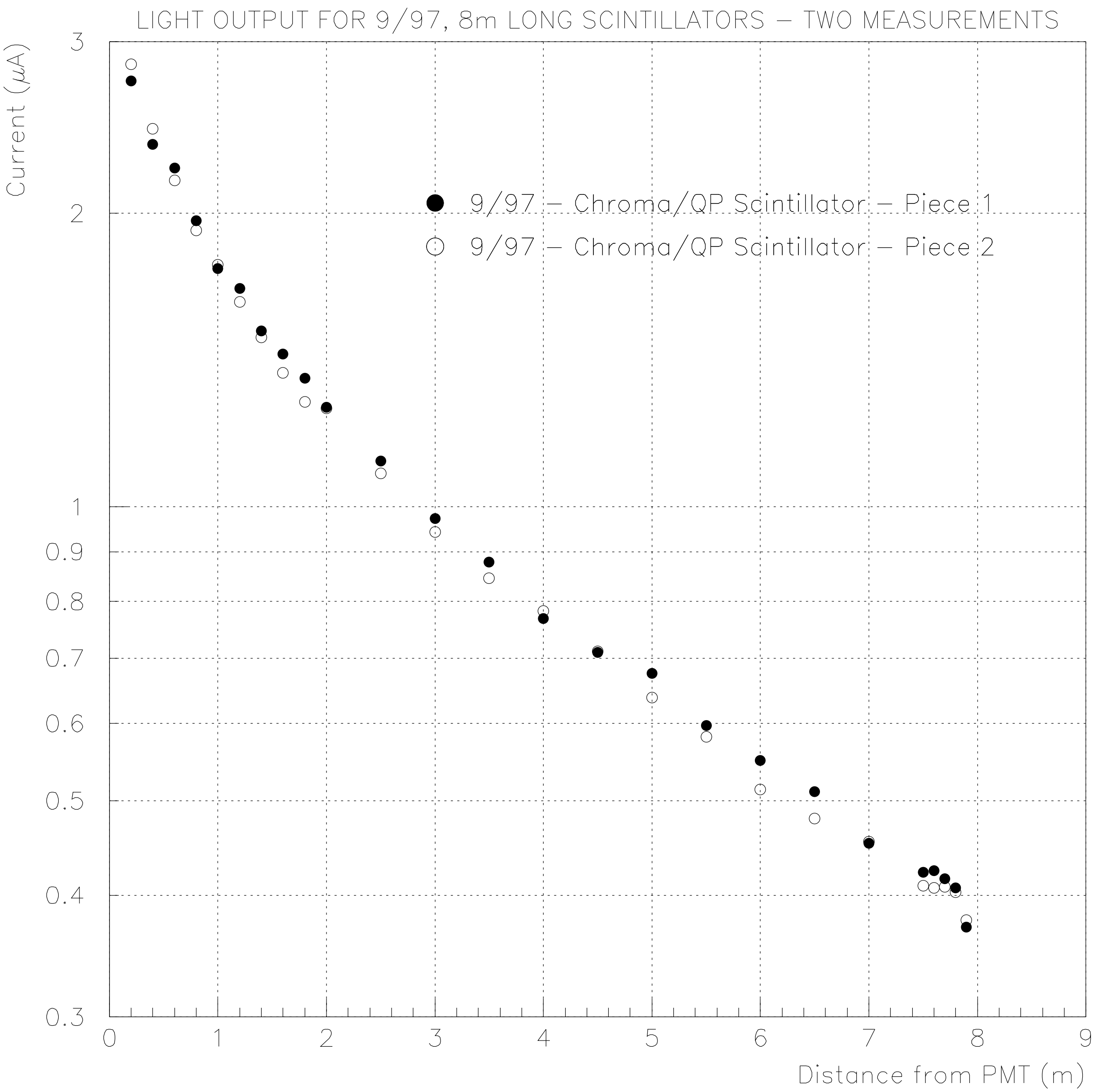

Figure 7: Light output comparison as a function of distance from the PMT for two pieces of eight meter long Chroma/QP scintillator produced in September 1997. The consistency of the result shows the uniformity of the produced scintillator. The Y-axis has an arbitrary multiplicative factor of 10.

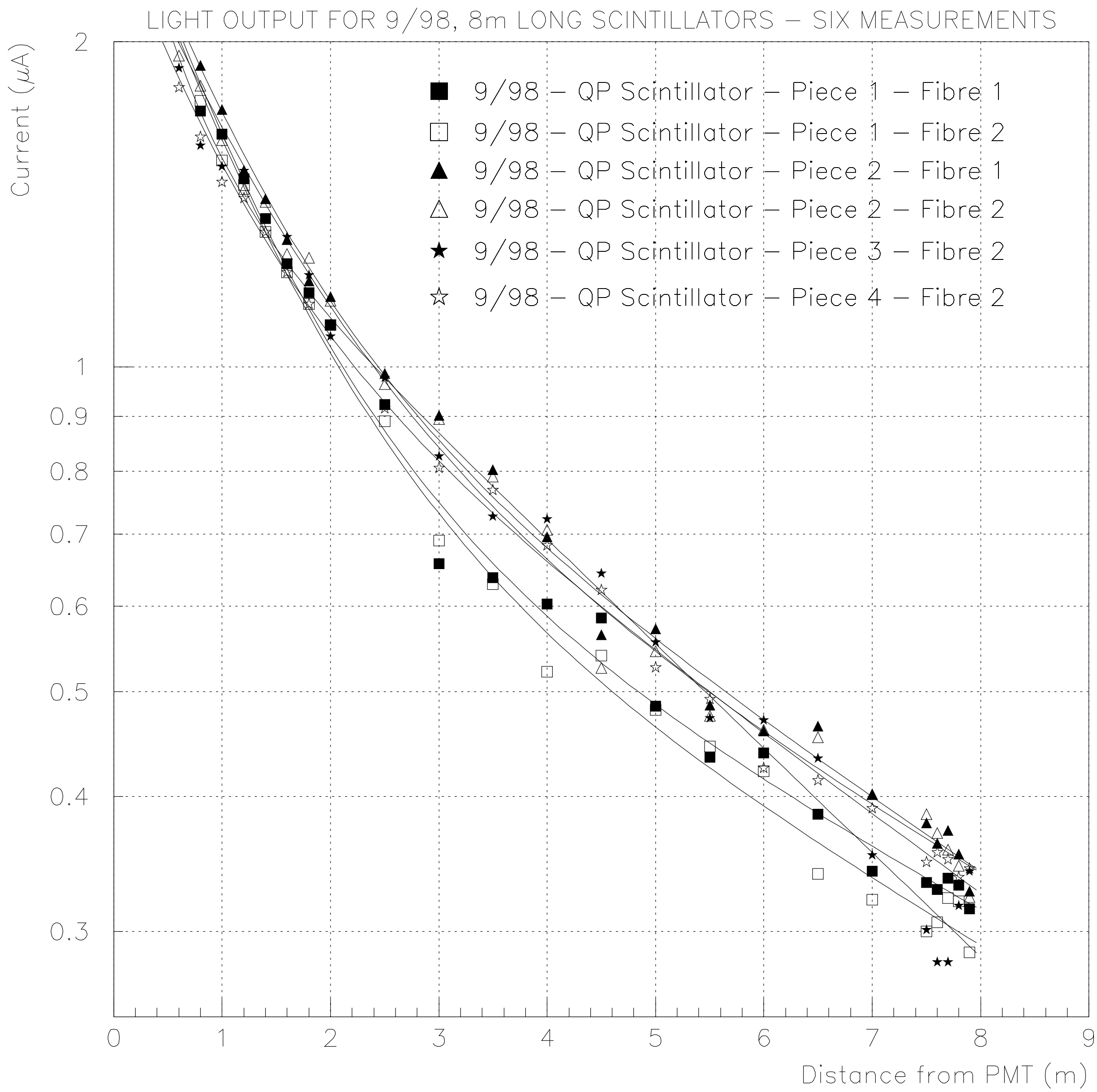

Figure 8: Light output comparison as a function of distance from the PMT for four pieces of eight meter long QP scintillator produced in September 1998. The inconsistency of the result shows the non-uniformity of the produced scintillator. The Y-axis has an arbitrary multiplicative factor of 10.

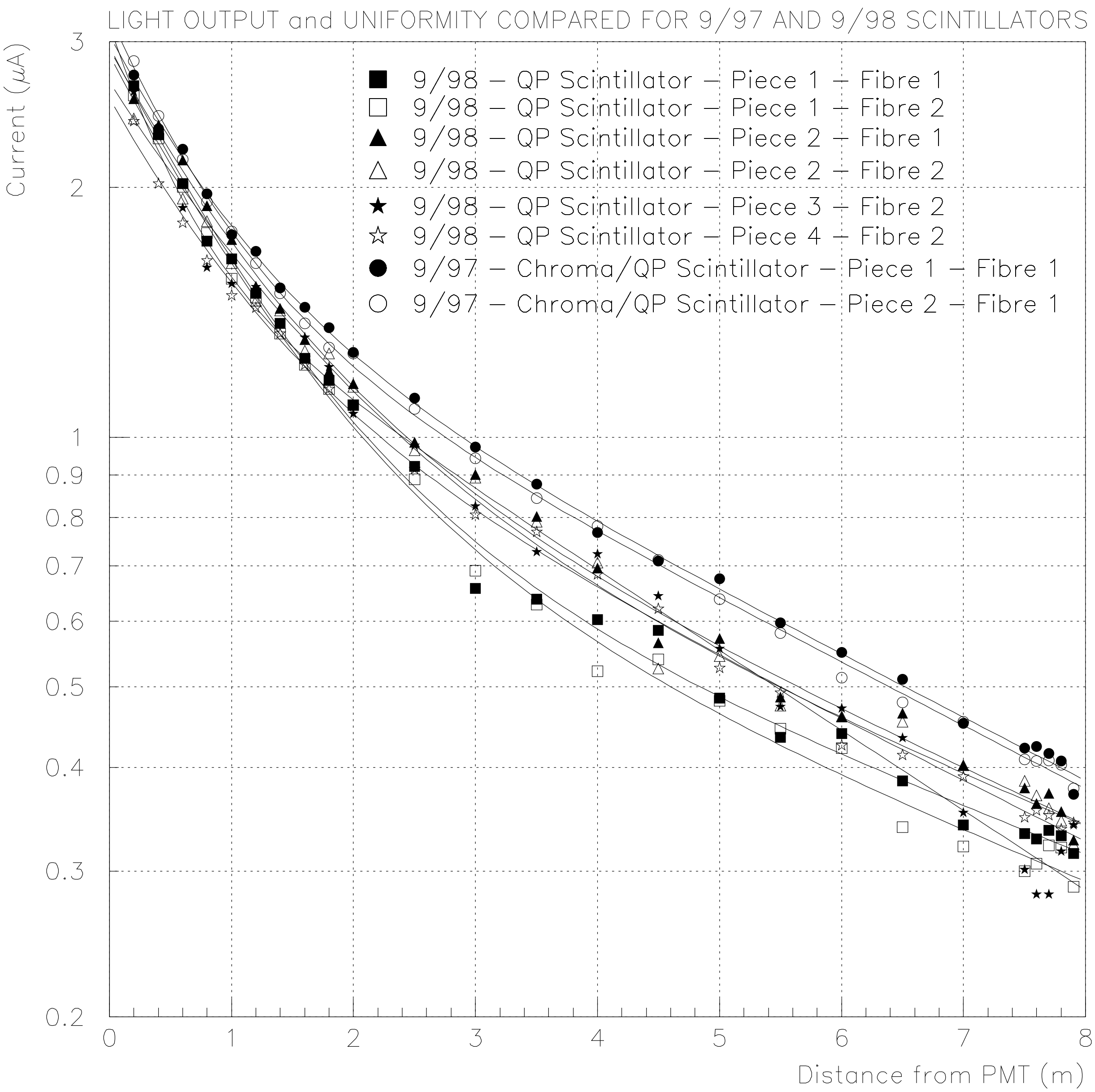

Figure 9: Light output comparison as a function of distance from the PMT for two pieces of Chroma/QP 9/97 batch scintillator and four pieces (six measurements) for QP 9/98 batch scintillators. The consistency and inconsistency of the measured result for these two batches shows the uniformity and non-uniformity of the produced scintillator. The Y-axis has an arbitrary multiplicative factor of 10.

20mm wide with a hole in the middle. The company could not produce the scintillator with TiO_2 coextrusion. The scintillators from RDN without coextrusion were wrapped in Tyvek and light output was compared with QP produced scintillator.

1. Light output using 8m long RDN scintillator piece wrapped in tyvek with fibre inserted through the dry hole was compared to 8m long cotxtruded QP scintillator with fibre in optical contact (using resin in the groove). It was found that while for most of the length (2m to 7m from PMT) the RDN gives nearly 35% extra light compared to QP, at the very far end (7.5m to 8.0m) it only gave 10%-20% extra light compared to QP sample.

2. Since the RDN scintillators had hole in the middle in which fibre was inserted one could compare light output for the case when fibre was optically coupled to the scintillator (resin in the hole) compared to the case when the fibre was not optically coupled (air gap between the scintillator and the fibre) . Several 70cm long pieces of scintillators were chosen and absolute light output at a distance of 8m from the PMT was compared for optically coupled case to non-optically coupled case using a radioactive source. Several different fibres were also used for both the cases. It was found that the light output for optically coupled condition was almost **1.70±0.05** times more than the non optically coupled condition. Although this was a very encouaging result in itself and would have given twice the light compared to QP sample, it was very soon realised that it was an impractical concept to think about resin through 8m long hole of little over one milimeter diameter when the total length of the scintillator used in MINOS is approximately 1,000 Kms.

3. Since RDN with smaller transverse dimension (2cm) and not optically coupled to the fibre definitely gave more light compared to larger transverse dimension (4cm) of QP scintillator optically coupled to fibre, we decided to check the light output for the case when the fibre is put in a groove on the side in the RDN sample and is optically coupled to the fibre. For this we took several 70cm long pieces of RDN sample and filled the original hole with resin and cured them. Grooves were made on one side with precision machine. The light output at 8m from the PMT, for the RDN scintillator with groove on the side was compared with QP produced scintillator optically coupled to the fibre. It was found that RDN with a groove on the side gives almost 30% more light compared to QP. But if the loss in light collection due to different dimensions of scintillator (a loss of 25% from 2cm by 1cm to 4cm by 1cm) is taken into account the two scintillators from QP and RDN gave almost identical light, under the identical condition.

Based on physics needs and the practicality of producing reasonable scintillator, we agreed to produce our scintillators with the followings specification as shown in figure 10.

1. DOW polystyrene with 1.0% PPO and 0.030% POPOP.

2. Width = 41.0±0.8mm. Thickness = 10.0±0.05mm.

3. Coextruded with 10% TiO_2 by weight with a groove on the side. The dimesion of the groove is, width = 1.4±0.15mm and depth = 1.5±0.25mm.

4. Temperature in the hopper between 400^0F and 410^0F.

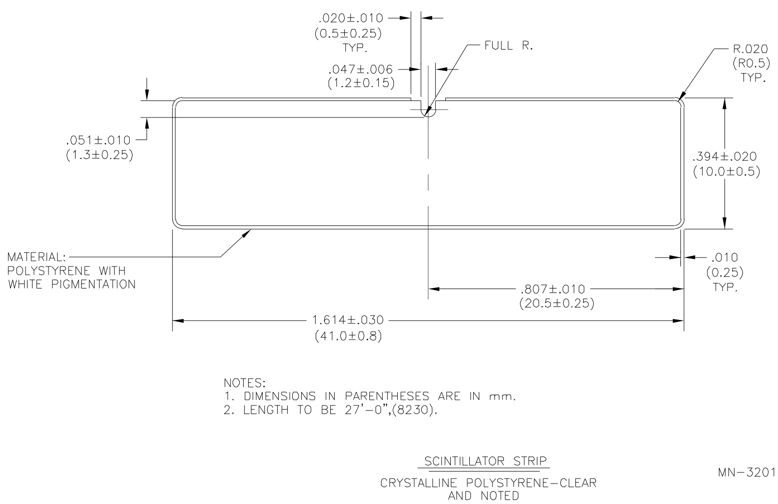

Figure 10: Detailed cross-section of a scintillator strip.

5. Polystyrene not purged with Argon while sitting in the gaylord.

1.1.6 Study of Russian Scitillator

In October of 1998, we received six different samples of Russian scintillators from ANL. These samples were 40mm wide, 10mm thick with a groove in the middle, identical to MINOS baseline design. The length of the scintillator pieces varied between 80 cm to 100 cm. The samples were either made with 1.0% PPT and 0.010% POPOP or with 1.5% PPT and 0.010% POPOP. Samples were either uncoated or coated with different coatings. Light output was measured for all the samples with same fibre and compared with scintillators developed in USA. Light output was measured using a 8m long Kuraray Y11(150), 1.0mm diameter fibre at intervals of 10cm between 7.1m to 7.9m from the PMT. The radioactive source was 5mm off-center. For sample numbers one to six as shown in table 3, only one piece of scintillator was available. For scintillators developed in USA (sample number seven to nine) several pieces were measured. The comparison is shown in table 3.

From the table above one can conclude that

1. For Russian scintillator, yellow combination of 1.5% PPT and 0.010% POPOP gives more

Sample No./ From	Fluor Composition	Color	Coating	Light Outpu
1/Russia	1.5% PPT + 0.010% POPOP	Yellow	No Coating Wrapped in Tyvek	1.09
2/Russia	1.5% PPT + 0.010% POPOP	Yellow	Single Coating Chemical ETCH	1.29
3/Russia	1.5% PPT + 0.010% POPOP	Yellow	Double Coating ETCH+TiO_2	0.80
4/Russia	1.5% PPT + 0.010% POPOP	Yellow	Combinative Coating TiO_2+PAINT	0.66
5/Russia	1.0% PPT 0.010% POPOP	Blue	Single Coating Chemical ETCH	1.11
6/Russia	1.0% PPO + 0.010% POPOP	Blue	Double Coating ETCH+TiO_2	0.76
7/USA 1997 Sept QP Two Step	1.0% PPO + 0.015% POPOP	Violet	Coextruded with TiO_2	**1.00**
8/USA 1998 June QP One Step	1.0% PPO + 0.030% POPOP	Yellow	Coextruded with TiO_2	0.95
9/USA 1998 Sep QP One Step	1.0% PPO + 0.030% POPOP	Yellow	Coextruded with TiO_2	0.90

Table 3: Light output comparison for various Russian and US developed scintillators, as compared to 1997 September, Chroma/QP two step scintillator.

light compared to blue scintilltor with 1.0% PPT and 0.010% POPOP.

With our earlier studies we know that 1.0% PPO and 0.010% POPOP is not an optimized combination. If PPO/PPT is 1.0% then the optimum amount of POPOP is between 0.015% and 0.030%. That was one of the reasons for us to chose 1.0% PPO and 0. 030% POPOP for developing our scintillator. We also know that with 1.5% PPO/PPT the optimum amount of POPOP is about 0.010%. So, the result that the yellow Russian scintillator gives more light compared to blue scintillator was expected and is not a surprise at all.

2. For both yellow and blue Russian scintillators, double coated scintillators give about 32-38% less light compared to single coated scintillators. It is possible that with double coating self absorption of light begins and that's why we see less light for double coated pieces. It was also observed that more the light produced, higher is the absorption of light in the double coated pieces of scintillators.

3. Combinative coating of TiO_2 plus paint gives even less light compared to double coating.

4. Single coating is better than scintillator with no coating but wrapped in tyvek. Anyhow for MINOS, the whole concept of wrapping the scintillator in tyvek is unrealistic, so it is a moot point.

5. The Russian scintillator with 1.5% PPT and 0.010% POPOP with single coating gives about 30% more light compared to 1997 Sept. Chroma/QP scintillator with 1.0% and 0.015% POPOP and almost 40% more light compared to the latest batch of one step scintillator (Sept. 1998) with 1.0% PPO and 0.030% POPOP.

6. Based on measurement of light output from these pieces and within statistical uncertainty of measuring just one piece each of Russian scintillators, one can safely conclude that "**RUSSIAN scintillator with 1.5% PPT and 0.010% POPOP and single coating is better than any QP developed scintillator**."

7. **A WORD OF CAUTION**: On closely examining the samples of Russian scintillators with single coating of chemical ETCH, it was found that the coating was very thin and could easily get scratched. Glue also wets the coating and then it is easier for coating to peel off. One would need to test a larger sample of this scintillator to satisfy whether using scintillator with such thin and fragile coating is at all practical for MINOS.

1.1.7 Study of Japanese Scintillator

The Japanese company Kuraray had provided us with some scintillators in late 1997 or early 1998. They were 20mm wide 10mm thick with a hole in the middle. Light output was measured for those scintillators and were compared with scintillators with identical dimension developed at RDN. The Kuraray scintillators gave 25% less light compared to RDN scintillator. Since we decided to choose 4cm by 1cm scintillator with groove in the middle for our baseline design the Kuraray company was less enthusiastic at that time. Recently, they wanted to develope some 40mm by 10mm scintillators with groove on the side for us. For this they first wanted us to

Sample Number	One	Two	Three	Four
Composition	DOW PS + 1.0% PPO + 0.010% POPOP	Japanese PS + SCSN-81	Japanese PS + 1.0% PPO + 0.010% POPOP	DOW PS + 1.0% PPO + 0.015% POPOP
Produced and Provided by	Kuraray Japan	Kuraray Japan	Kuraray Japan	CHROMA/RDN USA
Color Under UV Light	Violet	Blue	Violet	Violet
No. of Piece Measured	3	3	3	4
Variation in Light Output Among Samples	$\pm$1%	$\pm$3%	$\pm$3%	$\pm$4%
Comparison of Light Output	**1.00** 0.85$\pm$0.03	0.75$\pm$0.03 0.63$\pm$0.03	0.90$\pm$0.03 0.77$\pm$0.03	—— **1.00**

Table 4: Light output compared for different scintillators produced by Kuraray company. Light Output has also been compared with CHROMA/RDN produced scintillator.

test some of their 20mm by 10mm scintillators with hole in the middle. We provided Kuraray with DOW polystyrene, PPO and POPOP that was used to develope scintillators in USA. They developed three different kind of scintillators (20mm wide, 10mm thick with hole in the middle, no coating) with DOW PS + 1.0%PPO + 0.010% POPOP, Japanese polystyrene with SCSN-81 wavelength shifter and Japanese polystyrene with 1.0% PPO and 0.010% POPOP. Five samples, each one meter in length, of each of these scintillators, were send to us. Light output was measured for each of them and compared with the old RDN samples. The fibre used was Kuraray Y11(150), 1.0mm diameter. The light output was measured between 71.m and 7.9m from the PMT, at an interval of 10cm each. No inconsistency among data points were found. Light output was compared as average of readings between 7.5m and 7.8m (average of 4 data points) and average of all nine data points. The ratio of result among different samples, whether we compared average of four data points or all nine data points or intermediate number of data points (5, 6, 7), did not change. The results are shown in table 4.

Based on above measurement we conclude that:

1. The scintillator produced by CHROMA/RDN gives maximum light output. It is expected because it had 1.0% PPO and 0.015% POPOP compared to Kuraray produced scintillators with 1.0% PPO and 0.010% POPOP.

2. The Japanese polystyrene with 1.0% PPO and 0.010% POPOP gives 10% less light compared to DOW polystyrene with same amount of PPO and POPOP. This suggests that DOW polystyrene is better compared to Japanese polystyrene used in the product provided.

Sample Number	One	Two	Three
Composition	DOW PS + 1.0% PPO + 0.015% POPOP	DOW PS + 1.0% PPO + 0.030% POPOP	DOW PS 1.0% PPO + 0.015% POPOP
Produced By	Kuraray	Kuraray	CHROMA/RDN
Number of Piece Measured	5	5	4
Number of Fibres Used	2	2	2
Variation in Light Output Among Samples	±2%	±3%	±4%
Comparison of Light Output	0.85±0.03	0.96±0.04	**1.00**

Table 5: Light output for Kuraray produced scintillators with PPO/POPOP concentration suggested by us, compared with light output from CHROMA/RDN produced scintillators.

3. The Japanese polystyrene with SCSN-81 fluor gives 18% less light compared to Japanese polystyrene with PPO and POPOP. This suggests that PPO and POPOP is a better fluor compared to SCSN-81.

We provided our results to Kuraray's technical experts and based on our experience we suggested them to produce scintillators with 1.0% PPO and 0.015% POPOP and 1.0% PPO and 0.030% POPOP respectively. Kuraray produced scintillators with DOW polystyrene and the PPO and POPOP concentration that we suggested. Five one meter long piece of scintillators each for both combination of PPO and POPOP were delivered to us in late October 1998. The light output for these samples has been measured and compared with the light output from the original RDN sample. The results are shown in table 5.

Based on these measurements, we further conclude that:

1. The scintillator produced with 1.0% PPO and 0.030% POPOP gives approximately 15% more light compared to scintillator produced with 1.0% PPO and 0.015% POPOP, irrespective of the geometry of the scintillator produced. This is consistent with our light output measurement using Quick Plastic developed scintillators with varying amount of PPO and POPOP as shown in table 2 earlier.

2. The Kuraray produced scintillator with 1.0% PPO and 0.030% POPOP gives approximately as much light as Chroma/RDN produced scintillator with 1.0% PPO and 0.015% POPOP. In principle, it should have given more light. Since we see almost equivalent amount of light in these two samples within measurement errors, it is only fair to stress that it is very hard to reproduce the production process and we have to be flexible enough to accept ±10% variation in light output from different batches of scintillators.

Based on these results, we have asked Kuraray to produce 41mm by 10mm scintillator with a groove on the side and coextruded with TiO_2, using Dow polystyrene, 1.0% PPO and 0.030% POPOP. Kuraray has agreed to do so and provide us with the next batch of scintillator by 20th of Dec. 1998.

1.2 Fiber R&D

We have studied wavelength shifting fibres(WLS) from two different vendors, Bicron and Kuraray respectively, and have measured light output, uniformity and the attenuation length for these fibres. We have also studied Kuraray fibres of different diameter (0.7mm, 0.8mm, 0.9mm, 1.0mm, 1.1mm, 1.2mm and 1.5mm) for relative light output. The study with smaller diameter fibre (0.7mm and 0.8mm) was specially done to explore the possibility of using Hamamatsu L16 phototube or DEP hybrid phototube. Since then, based on our study, we have decided not to use the Hamamatsu L16 phototube. The DEP hybrid photodetector remains an open issue at this stage. We have also studied light output for one fibre versus the case of two fibres using the same transverse granularity of the scintillator. It was felt at one stage that if one needs more light from the far end of the fibre, one could use two fibres instead of one. Based on our study of the light output for one fibre versus two fibres, for different diameter fibres, this option has also been dropped in favour of larger diameter (1.2mm) fibre. We have also measured light output for 10meters long "J" shaped and 17meters long "U" shaped fibres compared to single straight 8meters long fibre. Some of these were esoteric studies. Most of the results are discussed below.

1.2.1 Study of Bicron Fibres

The baseline design for the solid scintillator detector in september 1997 was prototyped using 1997 sample of Chroma/QP scintillator and 1.0mm diameter WLS fibre purchased from Bicron in summer of 1997. As shown in figure 11, it provided approximately 0.9 photoelectrons from the far end and 3.5 photoelectrons from the near end of the PMT. The summed average from both ends was approximately 3.0 p.e. Although the collaboration decided that the light produced was adequate, it was obvious that we must pursue our R&D efforts towards getting more light. Since then, we have received one more batch of Bicron WLS fibre of 1.0mm diameter. The light transmission for several pieces of new batch of Bicron fibre, pedestal subtracted current, as a function of distance is shown in figure 12. The fibres are very uniform. A double expenential was used to fit the data for each fibre for measuring the attenuation length. The short attenuation length for this set of fibres varies between 70cm to 80cm and the long attenuation length varies between 5.0m to 5.2m. The ratio of long to short attenuation length varies between 6.3 to 7.0. We have also measured the absolute light output at the far end using 8m long fibres and found that this particular batch of fibre gives nearly 35-40% more light at the far end compared to the old batch with which the first full scale prototype was built. This was definitely a significant improvement and also points that further improvements were possible.

1.2.2 Study of Kuraray Y11 Fibres

In december of 1997, Kuraray supplied us twelve samples of fibre, 100 meters each of four different diameters (1.0mm, 0.9mm, 0.8mm and 0.7mm), produced with three different fluor

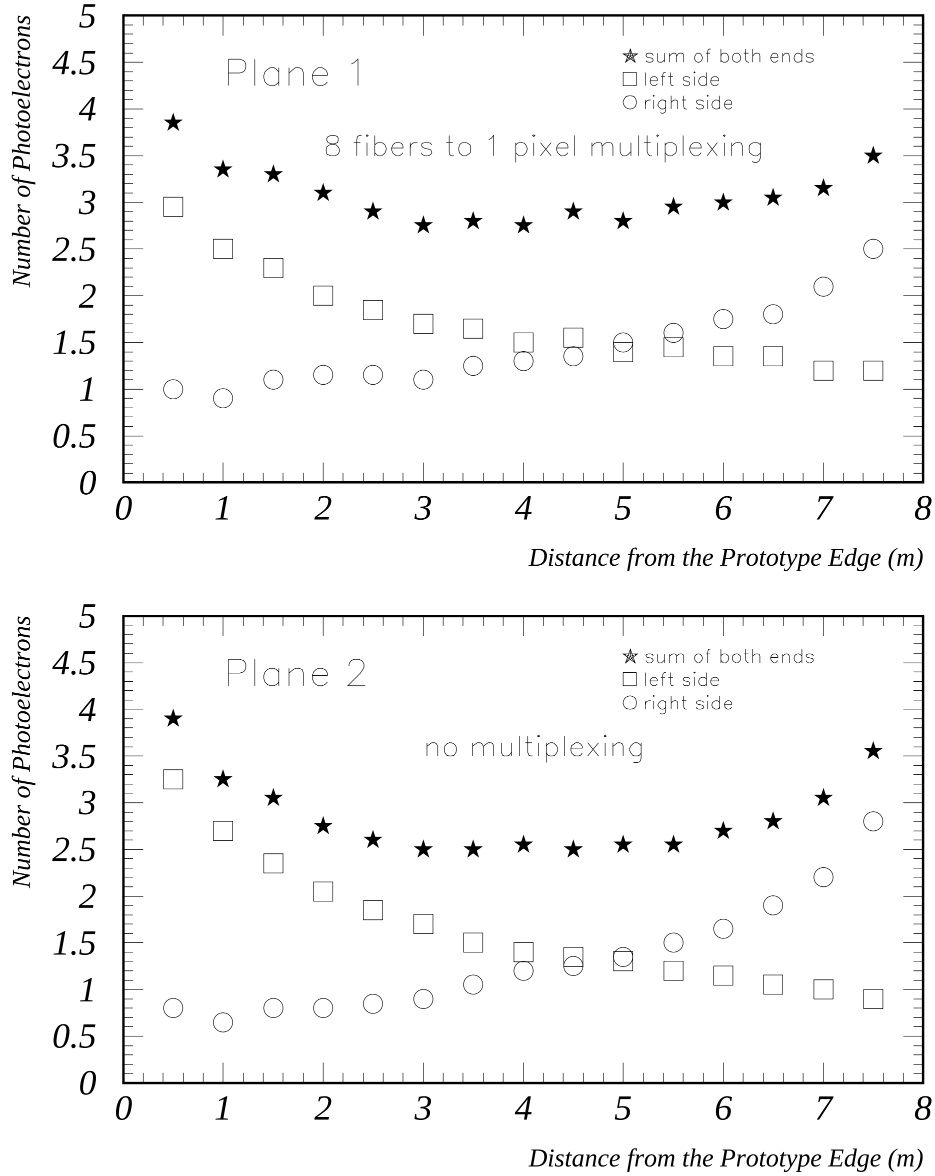

Figure 11: Result of photon yield measurements from the first full scale prototype built in september 1997. The top figure shows light yield for fibres from 8 strips multiplexed onto one pixel of the Hamamatsu PMT R5900U-00-M16. The bottom figure shows results for fibres connected separately to individual pixels.

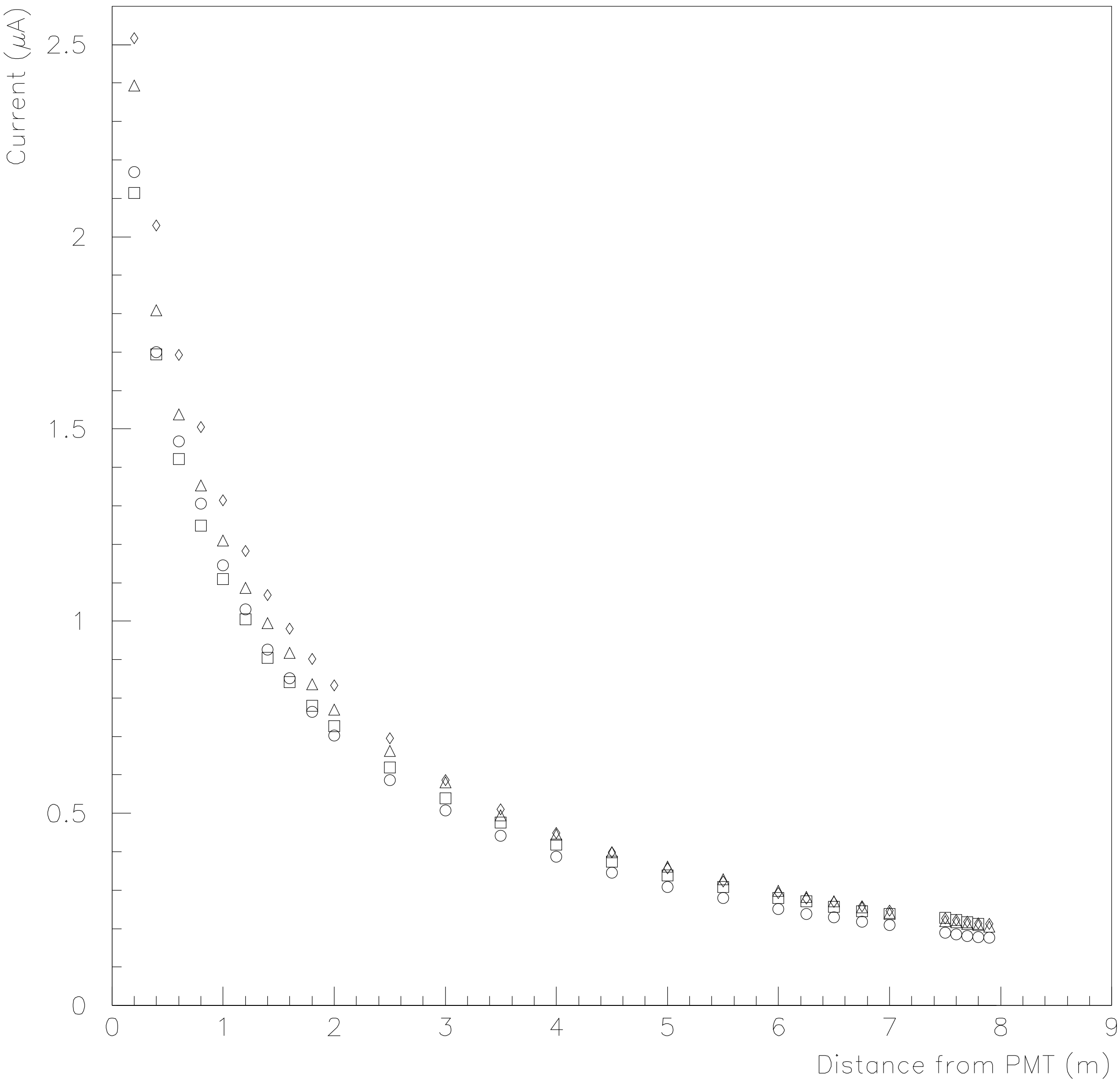

Figure 12: Light transmission through several eight meter long samples of wavelength shifting, 1.0mm diameter, Bicron BCF-91A fibres. The Y-axis has an arbitrary multiplicative factor of 10.

Factor	Influence On Light Output	Influence On Attenuation Length
Concentration of Y11 Dye	$\nearrow$	$\searrow$ Depends on Distance
Fiber Diameter	$\nearrow$	$\nearrow$ Depends on Distance

Table 6: General influence factor to WLS fiber performance.

concentrations (100ppm, 150ppm and 250ppm) of wavelength shifting dye called Y11. These are referred to as Y11(100), Y11(150) and Y11(250), respectively. We have mesaured the light output for these twelve different samples. Figures 13, 14 and 15, respectively shows the light transmission, pedestal subtracted current, as a function of distance, for fibres of different diameter for fluor concentration of Y11(100), Y11(150) and Y11(250) samples. One sees that the light transmission decreases with decreasing diameter. This is but natural. Figure 16, 17, 18 and 19, shows the pedestal subtracted current as a function of distance from the PMT, for Kuraray Y11(250), Kuraray Y11(150) and Kuraray Y11(100) for 1.0mm, 0.9mm, 0.8mm and 0.7mm diameter fibres respectively. We see that for 1.0mm diameter fibres, fibre with Y11(250) concentration of dye gives almost the same amount of light as fibre with Y11(150) at the near end of the PMT but as the distance from PMT increases, the light output for fibre with Y11(250) concentration decreases compared to fibre with Y11(150). One would have naively expected that if light transmission depended on the amount of WLS dye, then 1.0mm fibre with Y11(250) concentration would have produced maximum amount of light. But that is not the case. According to the Kuraray expert[3] on fibres, both, the green light generation in the Y11 fibre and attenuation length depends on the dye concentration and fibre diameter as shown in table 6. The fluor concentration of about 200ppm of Y11 is near to the saturated concentration from the point of view of light generation. Thus we see that although 1mm diameter fibre with fluor concentration of Y11(150) and Y11(250) generate almost the same amount of light, due to difference in attenuation length we observe more light with fibre with Y11(150) concentration. We have measured that the fibres with Y11(100) concentration generate the least amount of light for all possible diameters. Hence fibres with Y11(100) fluor concentration was not studied further.

Relative light output as function of diameter for Kuraray Y11(150) and Kuraray Y11(250) is shown in table 7. These were absolute measurements with 8m long fibres and 70cm long scintillator using a Sr^{90} source at the far end of the fibre from the PMT.

It suggests that the light output for Kuraray Y11(150) varies roughly proportional to the square of the diameter where as for Kuraray Y11(250), it varies directly proportional to the diameter. One explanation could be simply the problem of blue light absorption across Y11 fibre. The possibility of green light generation from blue light by crossing the Y11 fibre may vary between diamter and square of the diameter, depending on the whether the dye concentration is high or low respectively. For high concentration of Y11 fluor, 100% of blue light will be absorbed at the surface of the Y11 fibre. So the possibility of green light generation will be proportional to the diameter. But for low concentration of Y11 fluor, all blue light will not be absorbed at the surface of the Y11 fibre, hence the probability of green light generation will be proportional

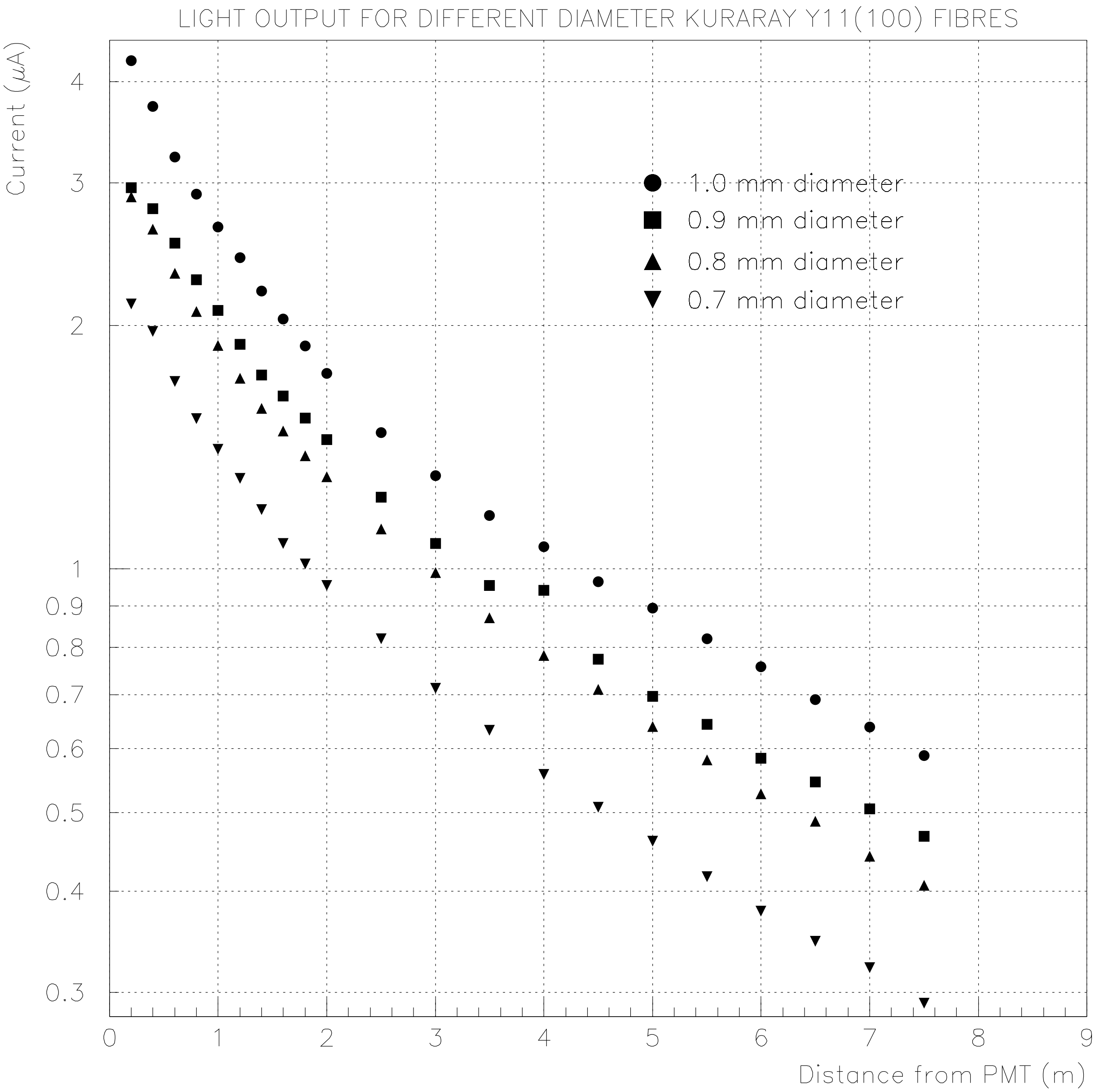

Figure 13: Light transmission for Kuraray Y11(100) fibres with different diameter. Light transmission goes down as the diameter increases. The Y-axis has an arbitrary multiplicative factor of 10.

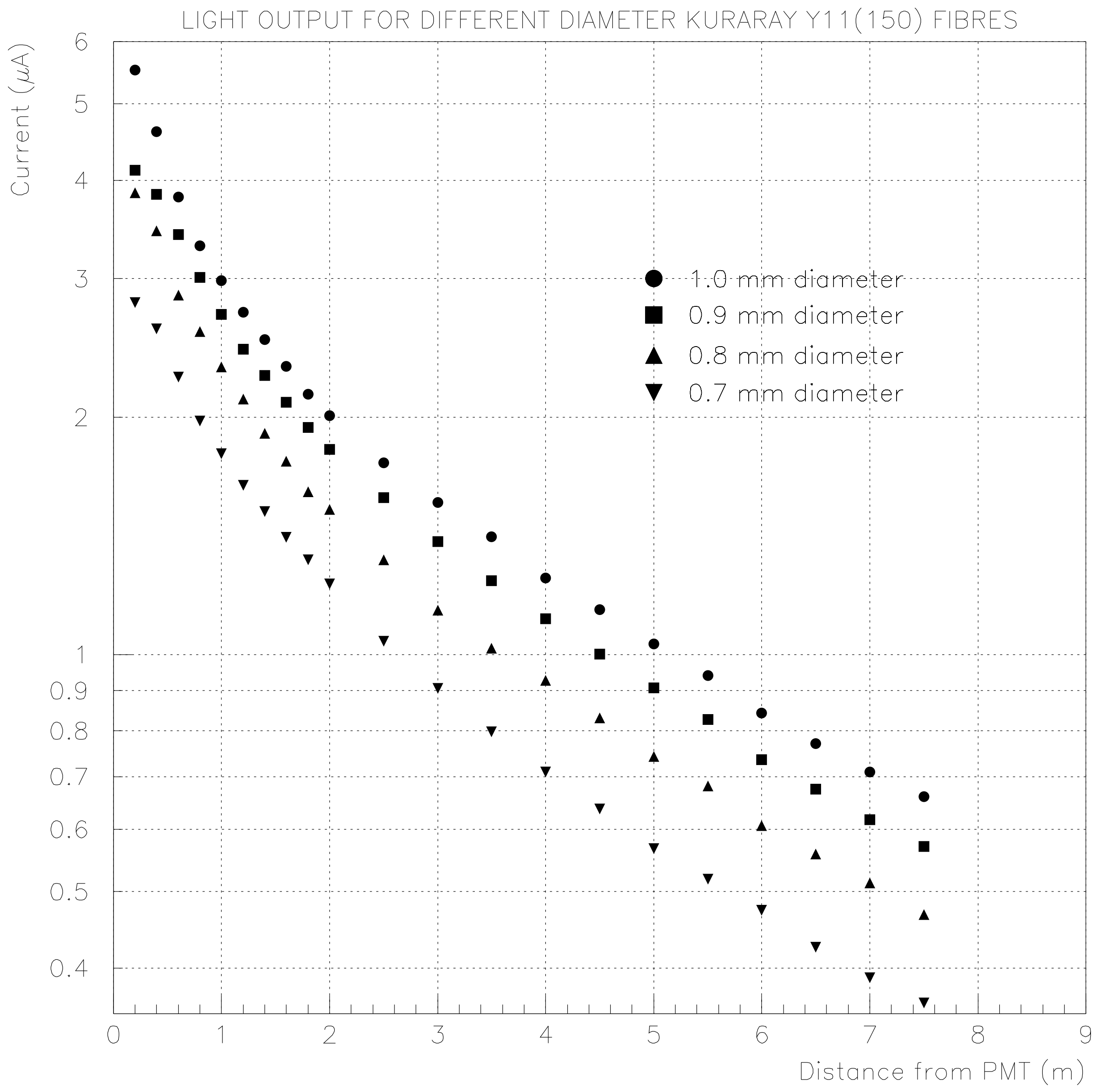

Figure 14: Light transmission for Kuraray Y11(150) fibres for 1.0mm, 0.9mm, 0.8mm and 0.7mm diameter respectively. The light transmission goes down as diameter decreases. The Y-axis has an arbitrary multiplicative factor of 10.

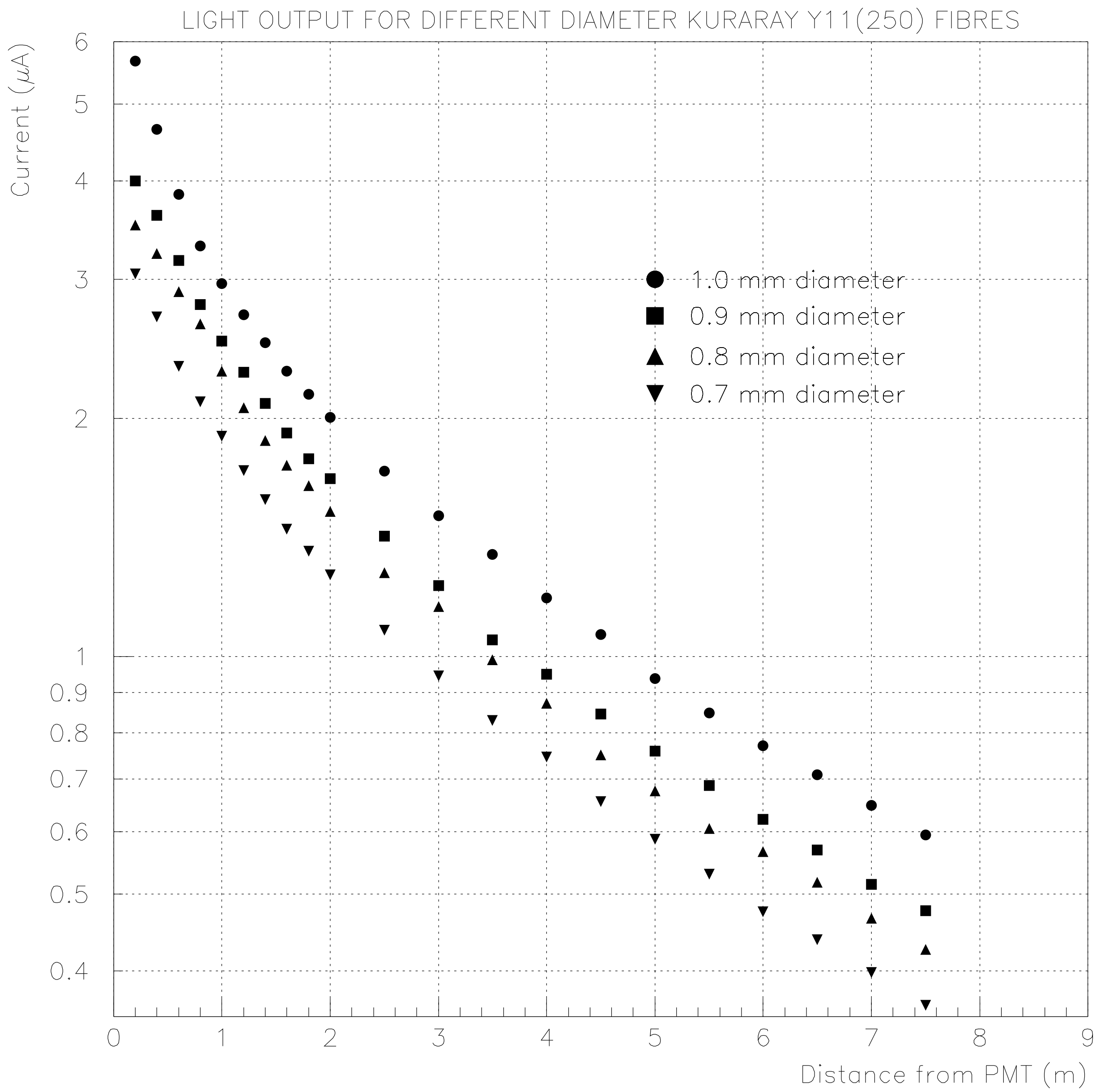

Figure 15: Light transmission for Kuraray Y11(250) fibres, for 1.0mm, 0.9mm, 0.8mm and 0.7mm diameter respectively. The light transmission goes down as diameter decreases. The Y-axis has an arbitrary multiplicative factor of 10.

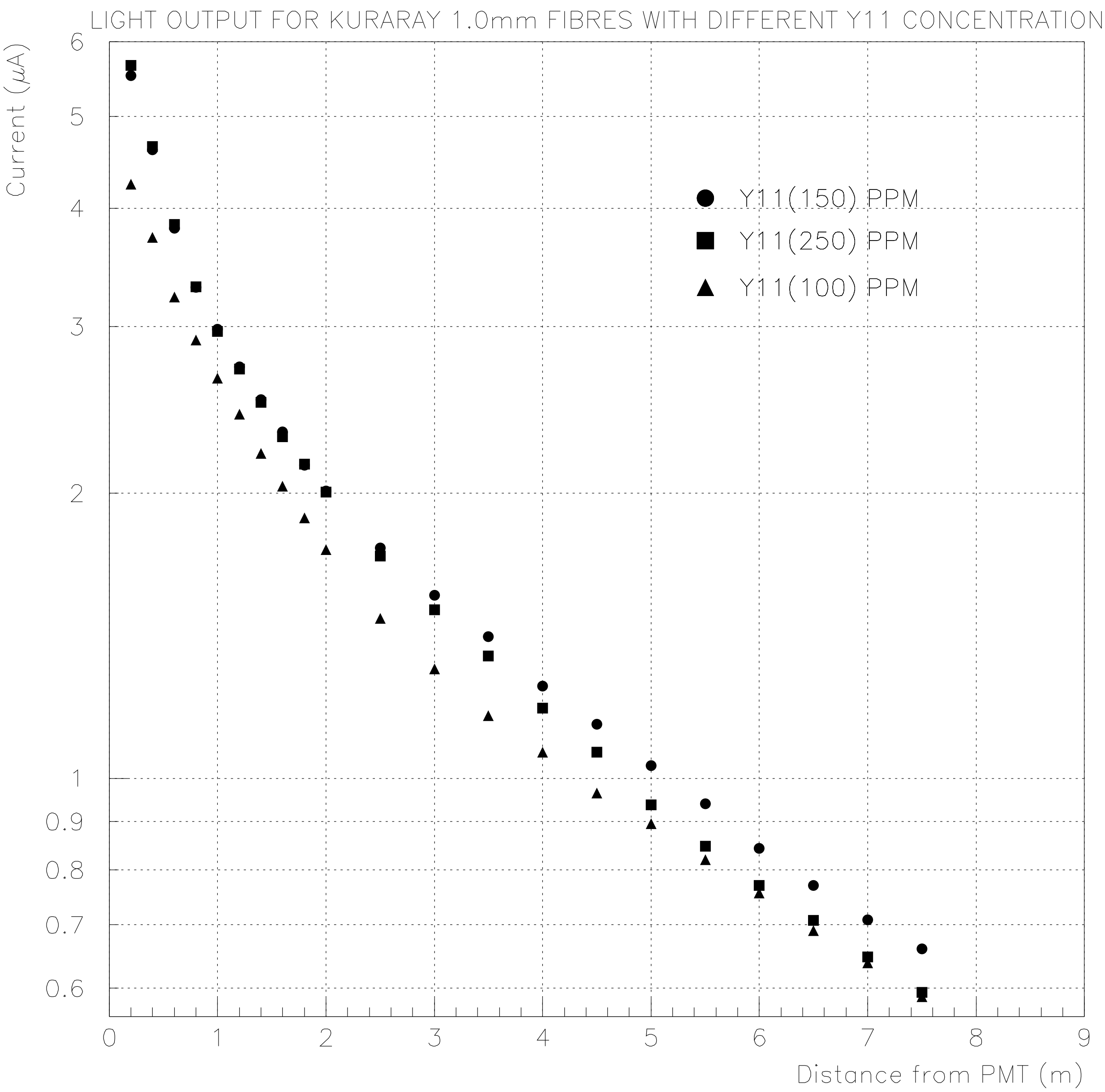

Figure 16: Light transmission in Kuraray 1.0mm fibre for differnt Y11 concentration. Circle represents Y11(150), box represents Y11(250) and triangle is for Y11(100). The Y-axis has an arbitrary multiplicative factor of 10.

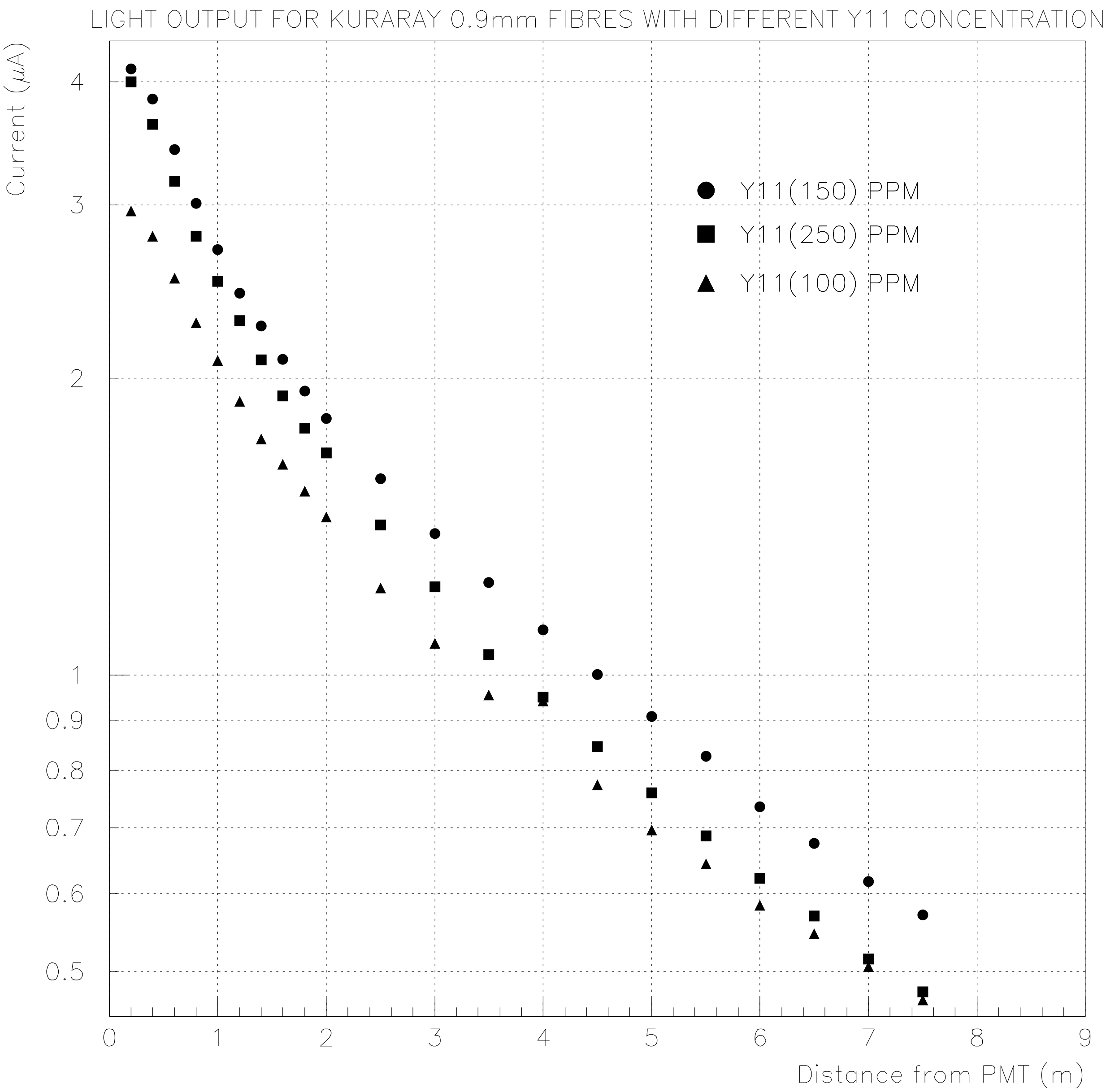

Figure 17: Light transmission in Kuraray 0.9mm fibres for different Y11 concentration. The Y-axis has an arbitrary multiplicative factor of 10.

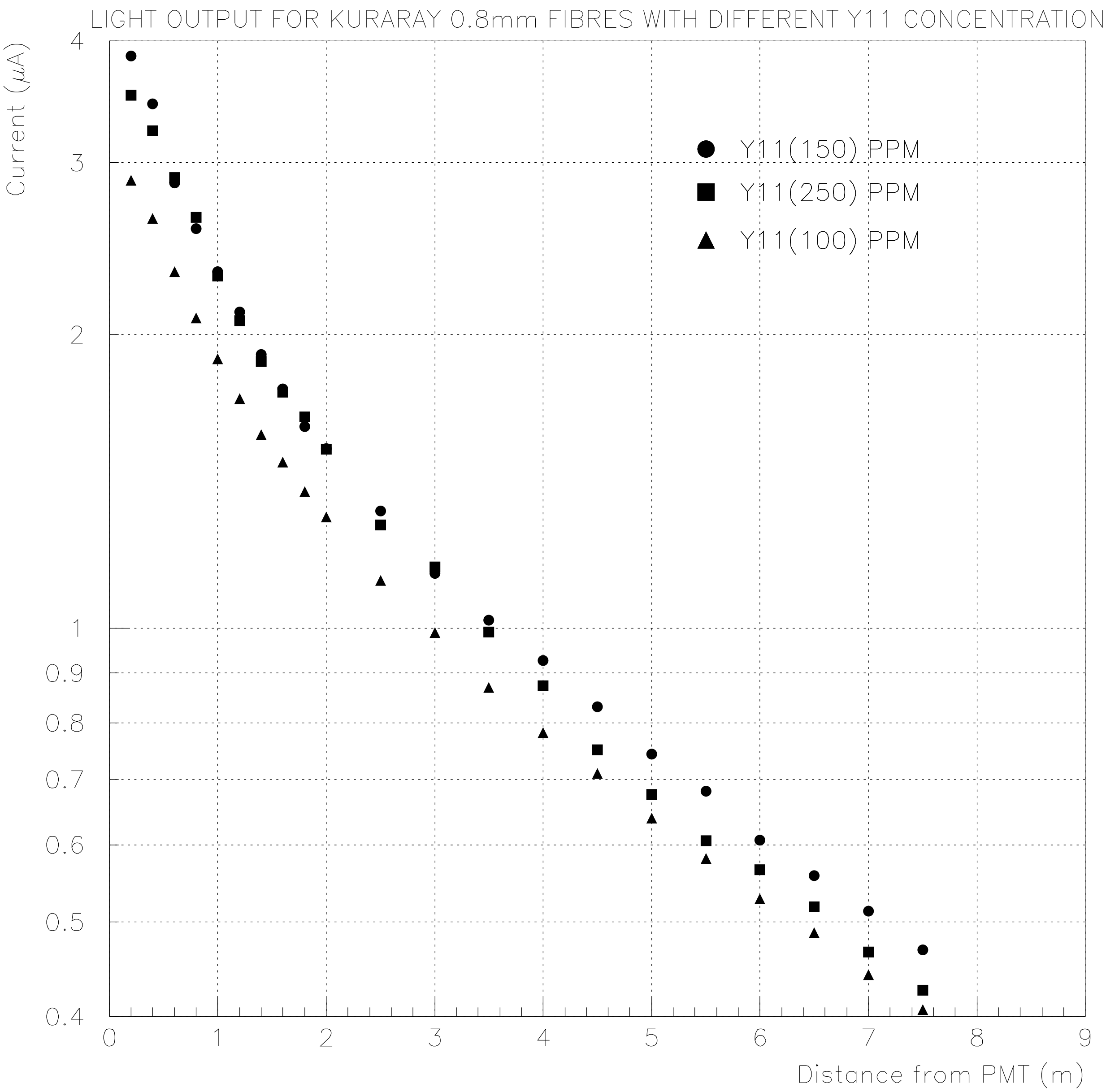

Figure 18: Light transmission in Kuraray 0.8mm fibres for different Y11 concentration. The Y-axis has an arbitrary multiplicative factor of 10.

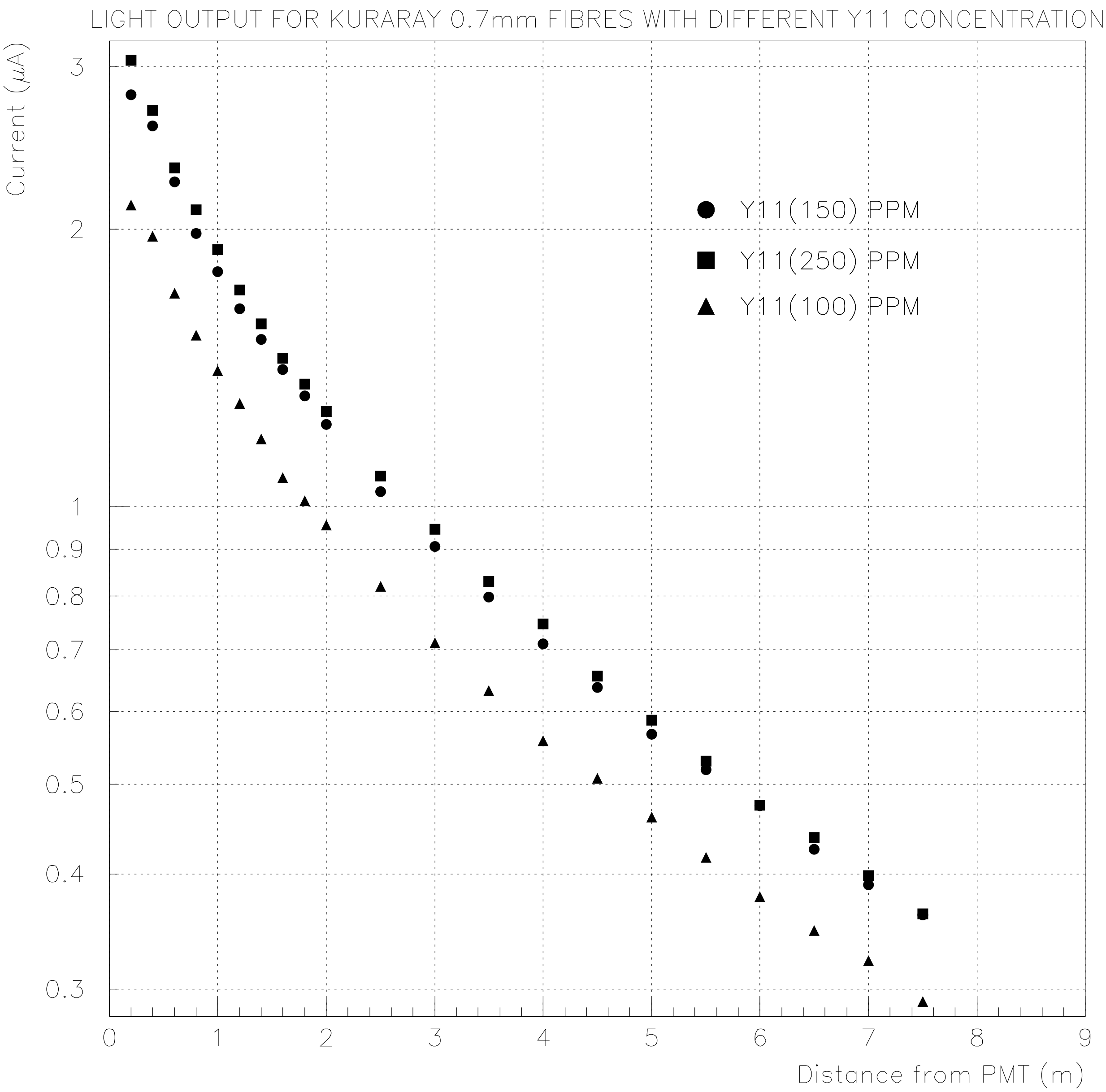

Figure 19: Light transmission in Kuraray 0.7mm fibres for different Y11 concentration. The Y-axis has an arbitrary multiplicative factor of 10.

Fiber	1.0mm	0.9mm	0.8mm	0.7mm
Kuraray Y11(150) 100m Batch, Dec 97	**1.00**	0.82	0.67	0.57
Kuraray Y11(250) 100m Batch, Dec 97	**1.00**	0.89	0.83	0.68

Table 7: Relative light output for different diameter Kuraray fibres compared respectively to 1.0mm diameter Kuraray Y11 fibre with the same fluor concentration.

Fiber	1.0mm	0.9mm	0.8mm	0.7mm
Kuraray Y11(250) 100m Batch. Dec. 97	0.84	0.75	0.70	0.57
Kuraray Y11(150) 100m Batch. Dec. 97	**1.00**	0.82	0.67	0.57
Kuraray Y11(150) 300m Batch. Feb. 98	0.77	—	—	—
Kuraray Y11(150) 1700m Batch. Feb. 98	0.87	—	—	—
Kuraray Y11(150) 1000m Batch. Jul. 98	1.00	—	—	—
New Bicron (9/97)	0.71	—	—	—
Old Bicron (Summer 97)	0.50	—	—	—

Table 8: Relative light output for different diameter Kuraray fibres, produced in different batches, with Y11(150) and Y11(250) wavelength shifter concentration, and Bicron fibres with 1mm diameter, compared to 1mm diameter Kuraray Y11(150) fibre from Dec. 97.

to $(\text{diameter})^{n}$ where $n>1$. The effect of attenuation length also needs to be taken into account for different diameter fibres. Since this study was conducted with small sample of fibres, the relationship between diameter and light output may not be exact. But it provided us with the idea that if one needs to increase light output we should go for larger diameter fibre and depending on the fluor concentration one can get much more light than just the linear increase in the diameter.

In table 8, we show the relative light output for different batches of 1.0mm diameter Bicron fibres and different batches of different diameter Kuraray fibres with Y11(150) and Y11(250) concentration compared to 1.0mm Kuraray Y11(150) fibre from Dec 97. We see that for 1.0mm and 0.9mm fibres the light output for Kuraray Y11(150) is more compared to Kurar[150qay Y11(250) but for smaller diameter fibres, 0.8mm and 0.7mm, the light output for both Y11 concentration is comparable.

The absolute light output was also compared with Bicron fibre. We found that Kuraray

Y11(150) 1.0mm diameter fibre from Dec 97 batch gave almost a factor of two more light compared to our baseline old Bicron sample and almost 40% more light than the best sample that Bicron has ever supplied. At this stage we decided to proceed with Kuraray Y11(150), 1.0mm diameter for our studies and ordered 2000m of Kuraray Y11(150) 1.0mm diameter fibre. This order of 2000m of Kuraray Y11(150) 1.0mm sample, was delivered in February 98, on two spools in length of 300m and 1700m respectively. The absolute light output was measured for these sample and the results are shown in table 8. Although the light at the near end of PMT were comparable, at the far end, the 300m sample gives about 77% light compared to the first batch while the 1700m batch gives about 87% of light compared to the first batch. This suggests that there might be large scale variation within different batches of fibres. To further test this hypothesis (and to make modules) we ordered 1000m of Kuraray Y11(150) in July of 98. The light output for this batch was comparable with the first batch of fibre from Dec. 97 as shown in table 8. At this stage, we contacted Kuraray with our results and asked for an explanation for the variation in light output from different batches of same diameter fibre with same fluor concentration. For different batches of fibres supplied, Kuraray provided us with their results on light output measurement, attenuation length measurement and light loss as the light travels through the fibre. Kuraray makes these measurements for every batch of fibre supplied. Their result on the measurements are in agreement with what we had measured. According to Kuraray expert[4] the possible explanation for the variation in light output is not due to dye concentration which is controlled to the accuracy of 0.5ppm; dust, impurity or any chemical properties, which are very well controlled, but is due to the drawing process. The fibres are produced by controlling some parameters at constant value in every batch. These parameters, like temperature and drawing speed are slightly different from batch to batch, which may give inter batch variation, largely in attenuation length and hence light output. These parameters could also vary within a batch which may produce intra batch variation in light output. Kuraray experts are still looking into all the data to figure out the most important parameter to improve inter batch uniformity. This tells us that we may have to live with atleast $\pm$5-8% variation in light output from different batches of fibre even if we establish specific criteria (like absolute light output, attenuation length etc) with Kuraray for fibre delivary.

1.2.3 Intra Batch Variation in Light Output for Kuraray Y11(150), 1mm diameter Fibre

We have looked at the intra batch variation in the light output for Kuraray Y11(150), 1.0mm diameter fibres for several batches. Figure 20 shows the light output(current) vs distance from PMT for twelve different fibres for Kuraray Y11(150) Feb 98 (1700m) batch. As we see the variation in light output is barely $\pm$5% and it includes the systematic error from measurement. Figure 21 shows the light output(current) vs distance from PMT for three different fibres for Kuraray Y11(150) July 98 (1000m) batch. As we see the variaition from fibre to fibre is minimal. It is our understanding from experience of working with Kuraray fibres that the intra batch variation is not large among the samples supplied.

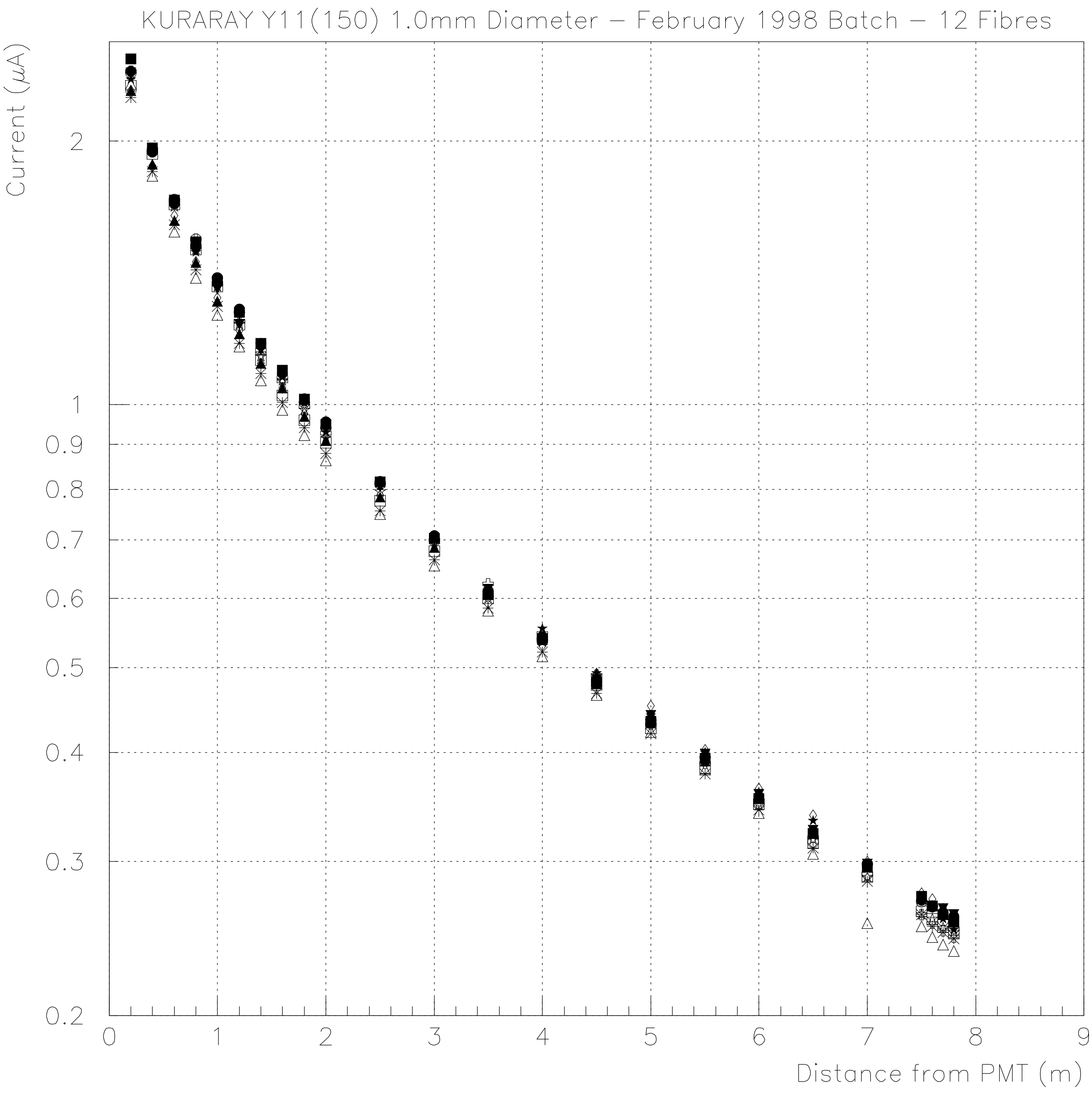

Figure 20: Variation in light output among twelve Kuraray Y11(150), 1.0mm diameter fibres from February 1998 batch. The intra batch variation in light output for this batch is within ±5%. The Y-axis has an arbitrary multiplicative factor of 10.

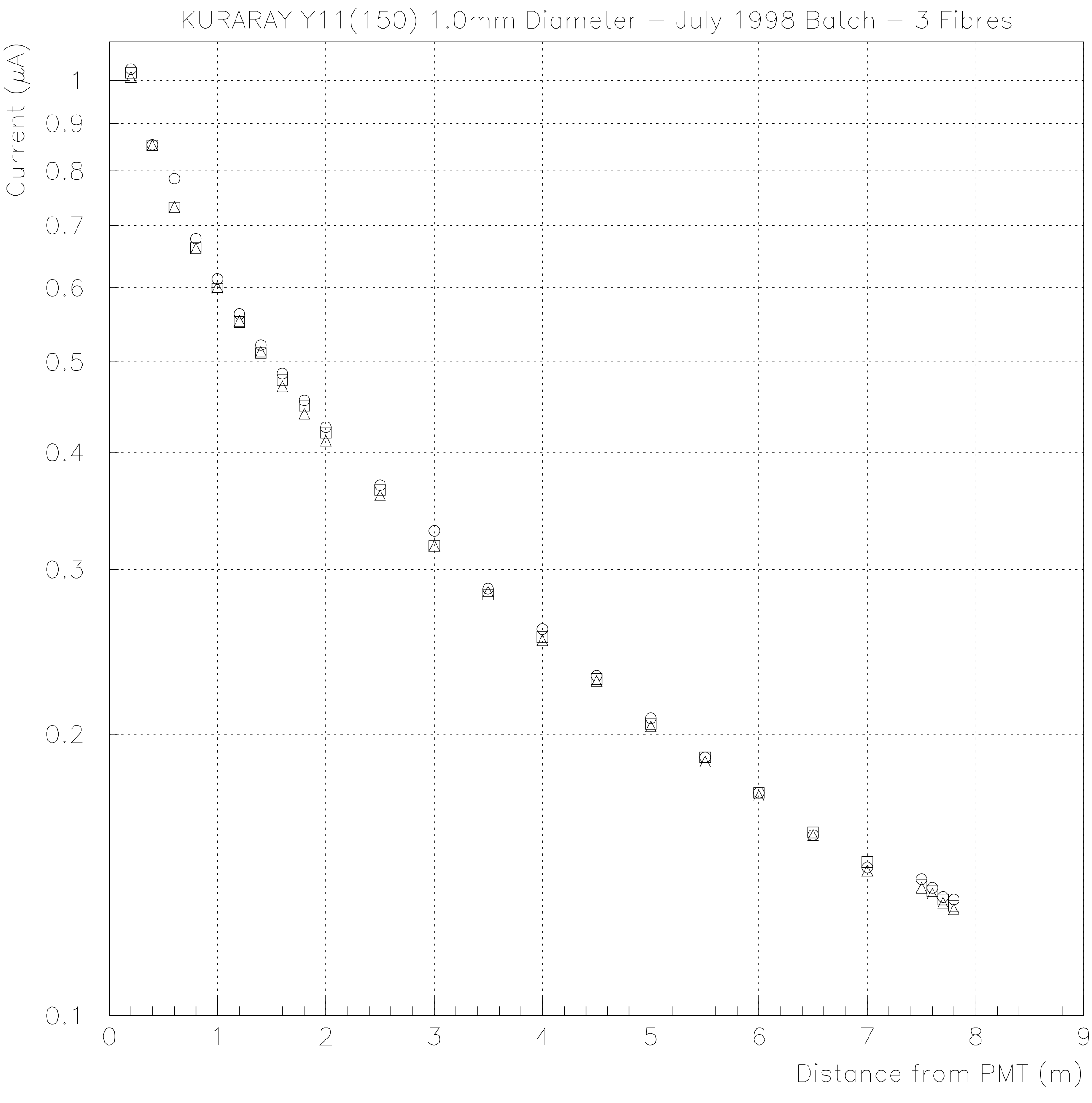

Figure 21: Variation in light output among three Kuraray Y11(150), 1.0mm diameter fibres from July 1998 batch. The intra batch variation in light output for this batch is within $\pm 2\%$. The Y-axis has an arbitrary multiplicative factor of 10.

1.2.4 Inter Batch Variation in Light Output for Kuraray Y11(150), 1mm diameter Fibre

We have also looked at the inter batch vatiation in light output for Kuraray Y11(150), 1.0mm diameter fibres. Figure 22 shows the light output(current) vs diatance for Kuraray Y11(150) from Feb 98(1700m) batch and Jul. 98 (1000m). As we see the light from the near end is almost identical but differs from the far end. Figure 23 shows ratio of light output for Kuraray Y11(150) for february 98 batch divided by light output for Kuraray Y11(150), august 98 batch. Close to the PMT, the ratio of light output is almost one but as the distance from PMT increases the ratio goes down by nearly 10%. This confirms that the attenuation length for feb 98 batch fibre is less compared to august 98 batch. We have measured the attenuation length for three fibres each from both the batches by fitting the data points using double exponential. We find that the average attenuation length for fibres from feb 98 batch (λ_2=5.3m) is approximately 10% lower compared to the average attenuation length(λ_2=5.8m) of august 98 batch. Our measurements are again consistent with data provided by Kuraray.

1.2.5 Light output for Two Fibres vs One Fibre

We have also compared absolute light output when we have used two fibres instead of one on the same transverse piece of scintillator. Such a study was done with Kuraray Y11(150), 0.7mm diameter and 1.0mm diameter fibres. This study was done primarily to explore the possibility of using two 0.7mm diameter fibres instead of one 1.0mm diameter fibre. If two 0.7mm diameter fibres together gave considerably more light compared to one 1.0mm diameter fibre then one can use two smaller diameter fibres, because the price for two 0.7mm diameter fibre is almost comparable to one 1.0mm fibre. That's why this study was limited to these two diameter fibres.

The study for light output was done when two fibres were placed close to each other in the same groove in the scintillator. Care was taken that when two fibres are placed in the same groove, side by side they should not touch each other. For this study, several 70cm long Quick plastic scintillator pieces were taken. The original groove was mechanically widened to accommodate two 1.0mm fibres. The light output was measured when one and two fibres were places in the groove. The study was done for both 0.7mm and 1.0mm fibres. The results are shown in table 9. We see that when two fibres are put together in the same groove we get about 65% extra light compared to one fibre only.

The study was also done when two fibres were places separately into two grooves. For this study, again, several 70cm long pieces of Quick platic scintillator were taken. The original groove was filled with resin and cured. It was also covered with a piece of tyvek. Two new grooves were mechanically made on the other face of the scintillator. The distance between the two grooves was approximately 2cm and the grooves were made approximately one centimeter from each edge. Light output was measured for one fibre separately and two fibres together. This study was also done for both 0.7mm and 1.0mm diameter fibre. The results are again shown in table 9. We see that when two fibres are placed separately we get about 85% to 90% extra light compared to one fibre only.

If one fibre would have absorbed all the light produced in the scintillator then we should not have seen any extra light by using two fibres. If the light trapped by the fibre was only a small fraction of the light produced in the scintillator then we should have seen twice the light

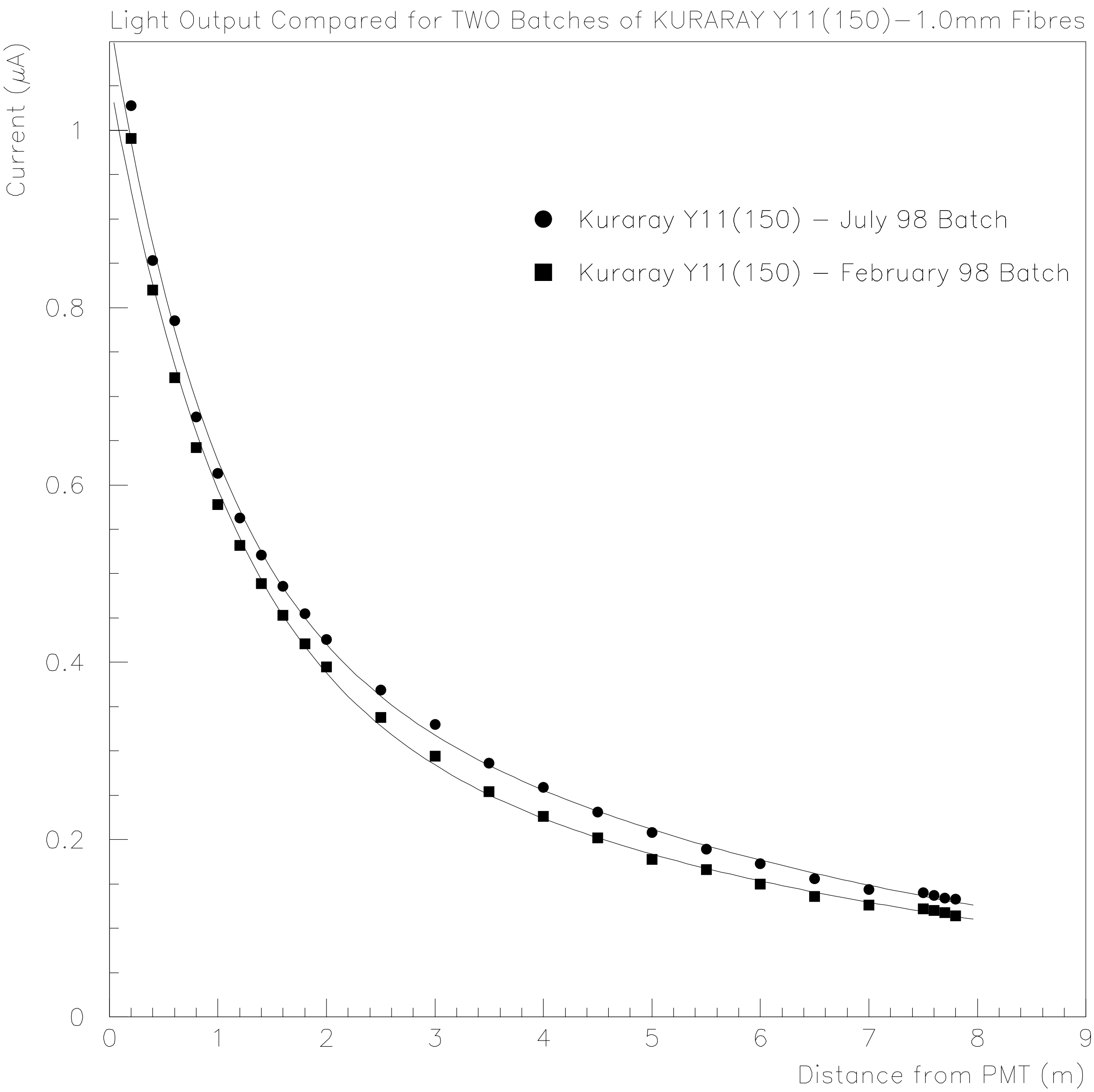

Figure 22: Variation in light output between two different batches of Kuraray Y11(150), 1.0mm diameter fibres. The fibre from July 98 batch gives almost 10% extra light compared to February 98 batch, for distance between 2 meters and 8 meters. The measured attenuation length for February 98 batch is less by almost 10%. The Y-axis has an arbitrary multiplicative factor of 10.

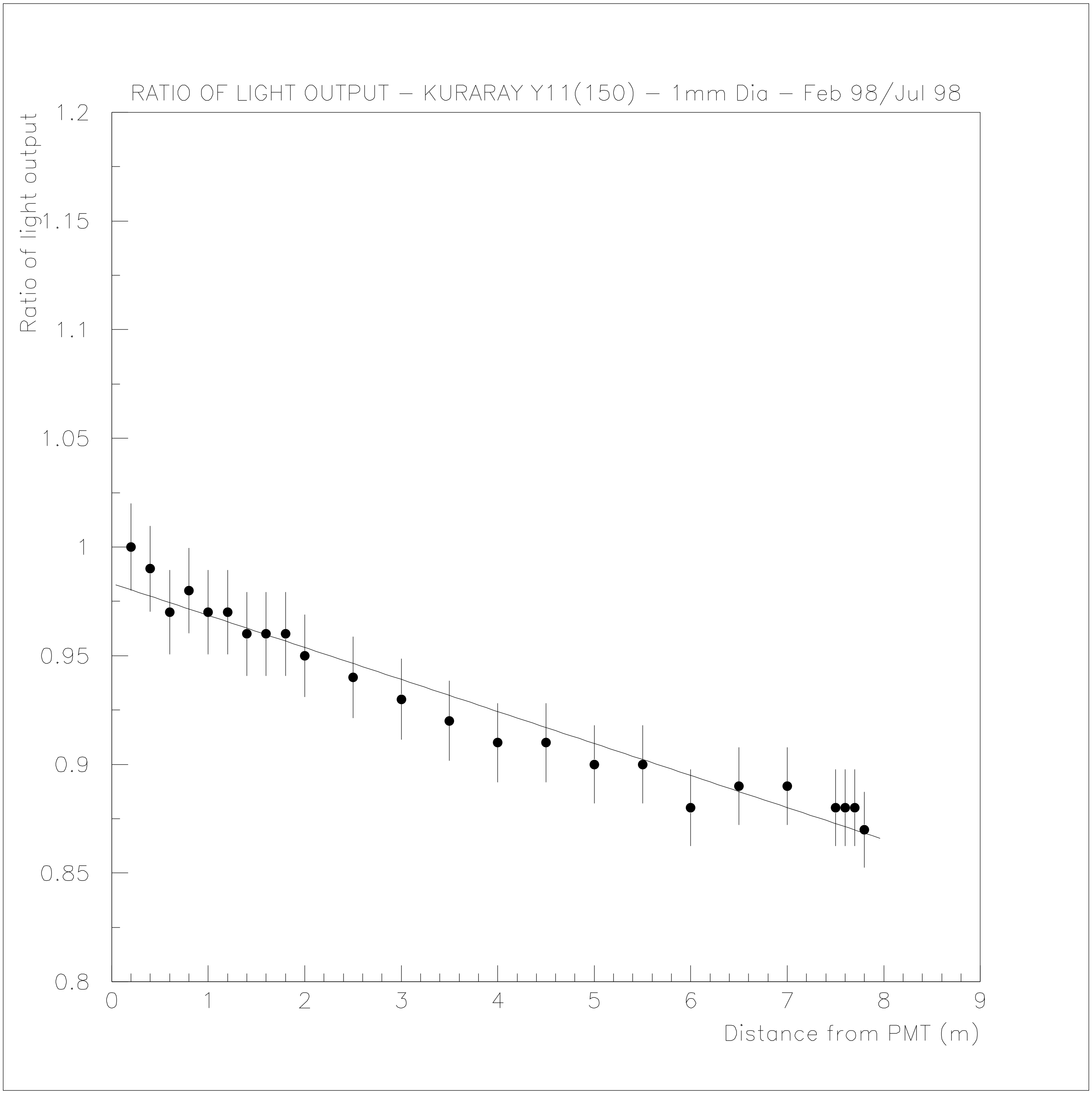

Figure 23: Ratio of light output as a function of distance for Kuraray Y11(150), 1 mm diameter fibre, for february 98 batch over july 98 batch.

Fiber/Diameter	Extra Light With Two Fibres In One Big Groove	Extra Light With Two Fibres In Two Separate Groove
Kuraray Y11(150) 1.0mm diameter	**1.65±0.10**	**1.90±0.20**
Kuraray Y11(150) 0.7mm diameter	**1.67±0.08**	**1.85±0.18**

Table 9: Light Output for two fibres vs one fibre for Kuraray Y11(150) fibre with 0.7mm and 1.0mm diameter respectively.

with two fibres. With two fibres places closer we see nearly 65% extra light while if they are separated we see 85-90% extra light. This suggests that when two fibres are placed very close to each other, each of them shadow the other and that's why we see nearly 15-20% less light when two fibres are placed in two separate grooves.

Although the result was encouraging, we decided not to use two smaller diameter (0.7mm) fibres because as shown in table 7, one 0.7mm fibre produces only 57% of light compared to one 1.0mm diameter fibre. With two 0.7mm diameter fibres we would have got as much light as single 1.0mm diameter fibre. Since 0.7mm fibre is extremely fragile and hard to handle it seems it will not be prudent to use two smaller diameter fibre either for reasons of cost effectiveness or light output. But if one need to increase the light output one could definitely use two 1.0mm diameter fibre and can get almost twice the light.

1.2.6 Light output with "J" shaped Fibres

At Ely collaboration meeting in june of 1998, Ken Heller from University of Minnesota, using a simple mathematical calculation based on our result on relative light gain from two fibres suggested that if one used a "J" shaped fibre instead of a straight 8m long fibre one should expect to get nearly 80% more light. The calculation uses the measured attenuation length from 6 to 8 meters to get the light attenuation. The only other factor is due to use of a "J" shaped fibres which is equivalent of using two fibres at the far end from the PMT. We have measured the light gain using two separated fibres to be about 1.8 times compared to one fibre. His contention[5] is that the factor of 1.8 for two fibres is determined by the clarity of the scintillator.

We have studied the possible increase in light from the very far end of a scintillator by using a "J" shaped fibre instead of a 8m long straight fibre. For this study Kuraray Y11(150) 1mm diameter fibre was used. To study the effct of "J" shaped fibres, four 70cm long QP scintillator pieces were taken. The original groove was filled with resin and cured. The original groove area was also covered with a piece of tyvek. Two new grooves were mechanically made on the other side of the scintillator pieces. The "J" shaped fibre was nothing but a 10m long fibre, which was bent in the "J" shape at the far end so that there would be two fibres in two grooves instead of one fibre in one groove, as is the case for the baseline detector. Two "J" shaped fibres were used for the study. The light output was measured with four pieces of scintillator using these two "J" shaped fibres. Light output was also measured using three different 8m long staight fibres with three different 70cm long pieces QP scintillator. The relative light output for "J" shaped fibre compared to a straight 8m long fibre is **1.60±0.10**. This is in relatively good agreement with the prediction above.

1.2.7 Light output with "U" shaped Fibre

At Ely collaboration meeting in june of 1998, Ken Heller from UoM using a simple mathematical calculation based on our result on relative light gain from two fibres also predicted that if one uses a "U" shaped fibre with two grooves in the scintillator, instead of one 8m long fibre in a single groove in the scintillator, one should expect to get atleast 3.6 times more light compared to a single fibre case. The reason is that a "U" fibre is like two separate fibres connected with each other. Since they are connected at the far end they behave like a perfect reflector. Since our presented number for two fibres was 1.8, the "U" fibre should give twice the time of 1.8, that is 3.6 times extra light.

The measurement for "U" fibres was done in the same fashion as for "J" fibres. We have used two separate "U" fibres. The total length of each "U" fibre was 17m. Four different scintillators were used with each "U" fibre to measure the light output. For single fibre measurement, we used three separate 8m long fibres and used three pieces of scintillator with each fibre. The relative light output for a "U" shaped fibre compared to a straight 8m long fibre is **3.55±0.35**, which is in very good agreement with the prediction.

1.2.8 Decision in Favour of Larger Diameter Fibre

In june of 1998, the light output from several protype modules made since september 1997 was evaluated. All of them used QP scintillators. Most of these modules except for one used Kuraray Y11(150) 1mm diamter fibres. Based on our experience with extruding scintillators it was obvious that it would be very difficult to get extra light from improved scintillator. The other choices were either to use DEP HPD tube or larger diamter fibre. Based on cost-benefit ratio and the R&D results already available within the collaboration, we decided to choose Kuraray Y11(150) 1.2mm diamter fibre as our baseline for detector construction. From results already presented earlier in this note, we knew that by using a fibre with 20% larger diameter we would definitely gain atleast 20% more light and at most 40% more light. This was based on our preliminary result that light output for Kuraray Y11 fibres increases between **radius** and radius^2.

We ordered 200m each of Kuraray Y11(150) fibre of diameter 0.9mm, 1.0mm, 1.1mm and 1.2 mm, respectively. These fibres were delivered in july 98. Several 8 metes long fibres for each of these diameter were scanned. Figure 24, shows the relative light output for three fibres for each of these four diameters. It is clear from the data that the variation in light output for the same diameter fibre is very small. The figure shows that the intra batch variation for Kuraray fibres are very small for all the four different diameters fibres.

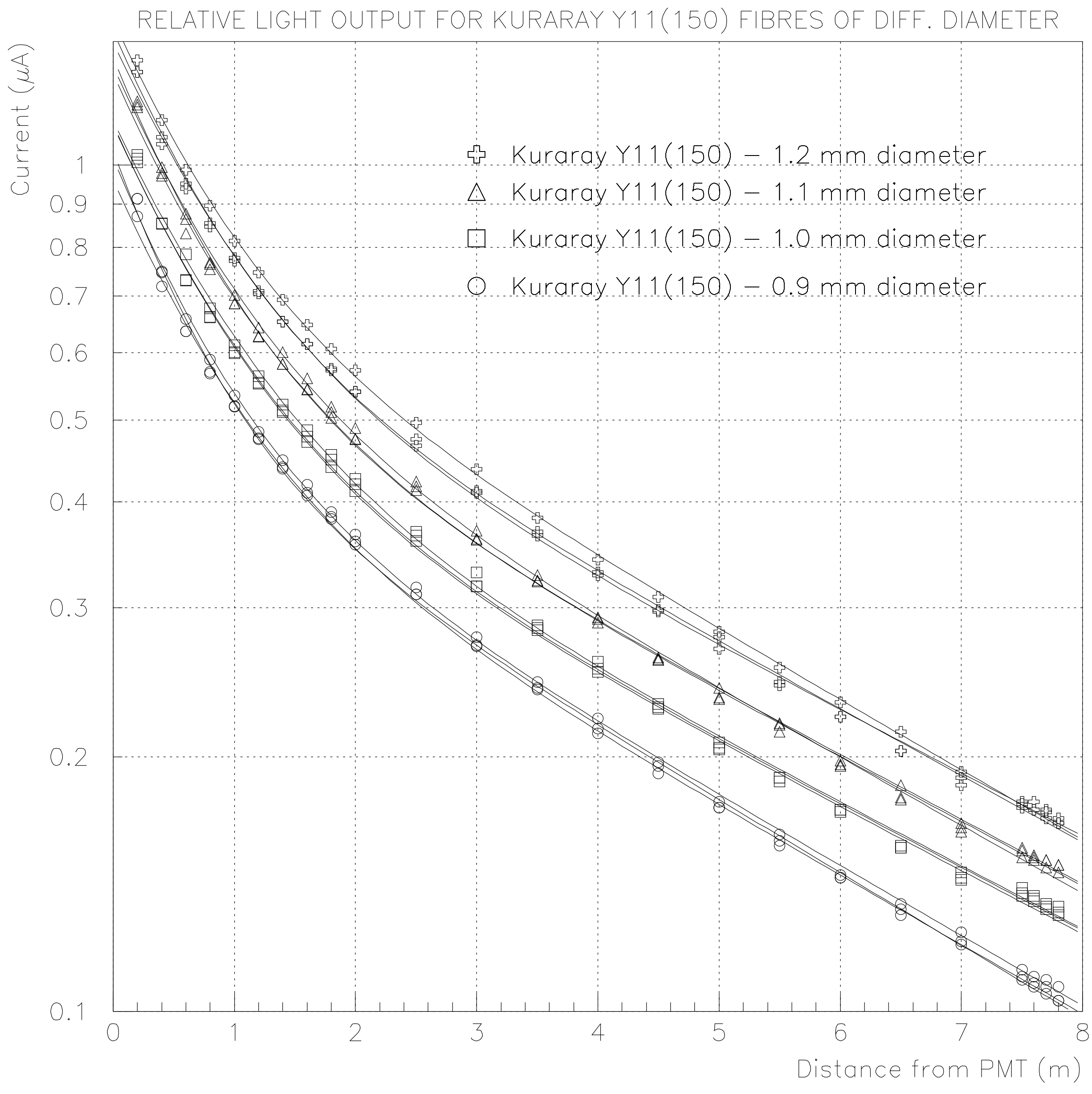

Figure 24: Light output as a function of distance from the PMT for Kuraray Y11(150) fibres of four different diameter. For each diameter three different fibres were measured and the results shown here. The Y-axis has an arbitrary multiplicative factor of 10.

Ratio of Fibre Diameter	Ratio of Light Output Distance from the PMT 0.2 m - 2.0 m - 7.0 m - 7.8 m
0.9	0.88 to 0.86 to 0.84 to 0.80
1.0	1.0
1.1	1.15 to 1.14 to 1.14 to 1.1.3
1.2	1.28 to 1.31 to 1.31 to 1.28
1.5	1.70 to 1.74 to 1.78 (at 4.5m)

Table 10: Ratio of light output as a function of distance from the PMT for different diameter Kuraray Y11(150) fibre from july 98 batch compared to light output for Kuraray Y11(150) 1.0mm diameter fibre from the same batch. As we observe the ratio of light output for any particular diameter is fairly flat over almost whole length (between 2m and 7m) of several 8 meters long fibres.

1.2.9 Study of Light Increase as function of Radius

We further ordered Kuraray Y11(150), 1.5mm diameter fibre. Because of larger diameter, 1.5mm diameter fibre could not be shipped on spool, as it will develope micro cracks. Several 5 meters long 1.5mm diameter fibre was sent by Kuraray in a tube. We also measured the light output for this fibre in the same way as we had done for other diameter fibres. After that the data point for different diameter (0.9m, 1.0mm, 1.1mm, 1.2mm and 1.5mm) Kuraray Y11(150) fibres from july 98 batch were divided by the data point for Kuraray Y11(150) 1.0mm diameter fibre, from the same july 98 batch. Thus 1.0mm diameter fibre serves as a reference fibre. Figure 25, shows the ratio of light output for different diameter fibre compared to light output for 1.0mm diameter. Table 10, shows the relative light outout for different diameter fibre compared to 1.0mm diameter fibre, as a function of distance from the PMT. We see that for most of the length of the fibre the ratio is fairly flat, although it varies little bit at the very near and the very far end from the PMT. If we neglect, very small variation at the very near and very far end from the PMT, we can easily conclude that the **Light Output for Kuraray Y11(150) fibre goes as** $\mathrm{RADIUS}^{1.4\pm0.1}$.

1.2.10 Intra and Inter Batch variation in Light Output for Kuraray Y11(150), 1.2mm diameter Fibre

In august 98, we further ordered 2000 meters of 1.2mm diameter Kuarary Y11(150) fibre. These were delivered on two spools in lengths of 900m and 1100m. Several fibres from both batches were measured. It was found that the light output from 900m batch of fibre was identical to july 98 batch of 200m of fibre. But the light output for 1100m batch of fibre was atleast 10% less compared to july 98 batch and august batch of 900m fibres. The results are shown in figure 26. Here the results are shown for three fibres from each batch. From figure 26, it seems that august 98 batch of fibre on 1100m spool was really bad. It not only shows less light compared to two other batches but also shows large intra batch variation. If this was true, it could be a

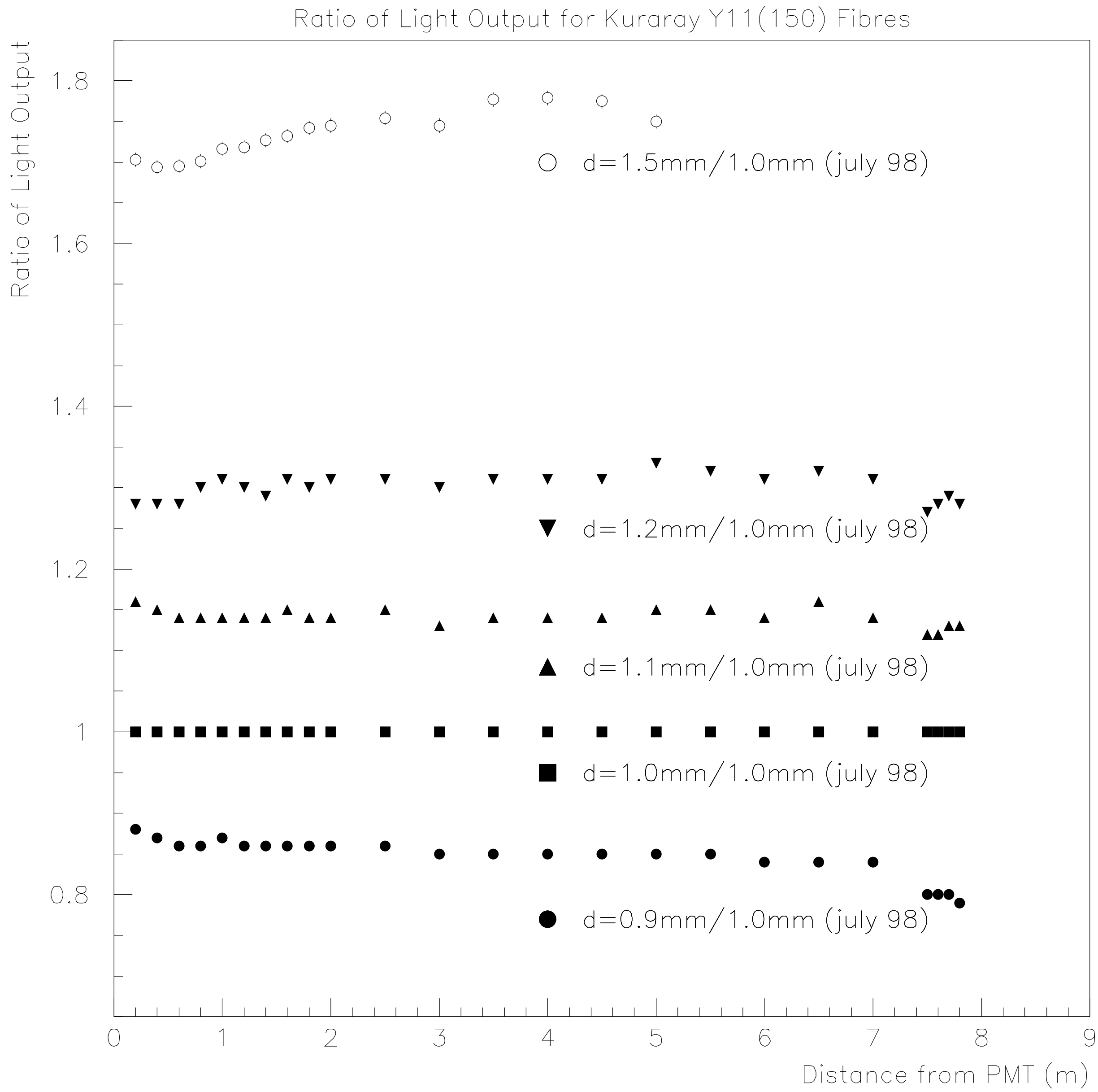

Figure 25: Ratio of light output as a function of distance from the PMT, for Kuraray Y11(150) fibres of five different diameter, compared to light output for 1mm diameter fibre of the same batch.

major concern for us. To check the quality further we tested several more fibres (6 fibres from 200m batch - july 98, 6 fibres from 900m batch - august 98 and 8 fibres from 1100m batch - august 98) from all the batches. The intra batch variation for july 98 batch of 200m and august 98 batch of 900m was minimal. The light output for these two batches were very comparable and thus the inter batch varition between these two batches were also in conformity with what is shown in figure 26. For 1100m batch of fibre, among the eight measured fibres, the intra batch variation for seven fibres was within ±5%, except for one fibre which shows less light throughout the length of the fibre. This particular fibre shows the least amount of light in figure 26. The measured attenuation length for this batch of fibre was almost 10% less compared to two other batches, which gets reflected into less light collected as the source of excitation is moved away from the PMT.

At this point Kuraray was contacted with these results and they provided their data for the measurement of attenuation length and light output for these three batches of fibres. The results from Kuraray are shown in table 11. At Kuraray, the attenuation length is measured by fitting 40 points from 100 to 300cm, far from excited points, using a blue LED and a bialkali PMT. The PMT output is measured by exciting at the point of 290 cm with the blue LED. Although, the measurement from Kuraray cannot be directly compared to our measurement, it is very clear from their measurement that the 1100 meter batch of fibre has the lowest measured attenuation length, which is consistent with our measurement. Kuraray experts were unable to answer the precise reasoning for this variation in light output. They requested us to send fibres from these batches and further studies are being done at Kuraray company in Japan. No result has been made available till now.

SOME THOUGHTS ON FIBRE QUALITY FROM KURARAY: From my personal experience with measuring atleast several hundreds of fibres of various types from Kuraray, one can say that the intra batch variation for Kuraray fibres is very small. In worst case scenario we have atmost seen ±5% variation within the batch. This also includes the systematics of the measurement. But in most of the cases the variation is within ±2-3%, which is very good. The inter batch varaition for some Kuraray fibres has seen to be large. One batch of 1.0mm fibre gave almost 20% less light compared to the best batch. The worst batch of 1.2mm fibre gave almost 10-12% less light compared to the best batch. But in most of the cases for both 1.0mm and 1.2mm diameter fibres, the difference between the batches are within ±5%. Again Kuraray has no concrete explanation on this batch to batch variation in light output, except that it depends on the drawing process of the fibre where certain parameters like temperature, drawing speed varies. More work is going on at Kuraray to answer these questions.

For the final delivary of fibres for building the detector, one would have to define certain parameters like attenuation length, light output etc, which Kuraray must meet. Kuraray in principal has agreed to meet those requirements but more R&D is needed to decide those exact parameters. We, in the MINOS collaboration are also developing test machines for automated measurement of fibre attenuation length and general characteristics of the fibre.

SOME MORE THOUGHTS ON FIBRE AND LIGHT OUTPUT: It is my believe that 1.2mm diameter fibre is the most optimum one for MINOS detector. It is possible that 150ppm concentration of Y11 may not be most optimum and we must test other Y11 concentrations

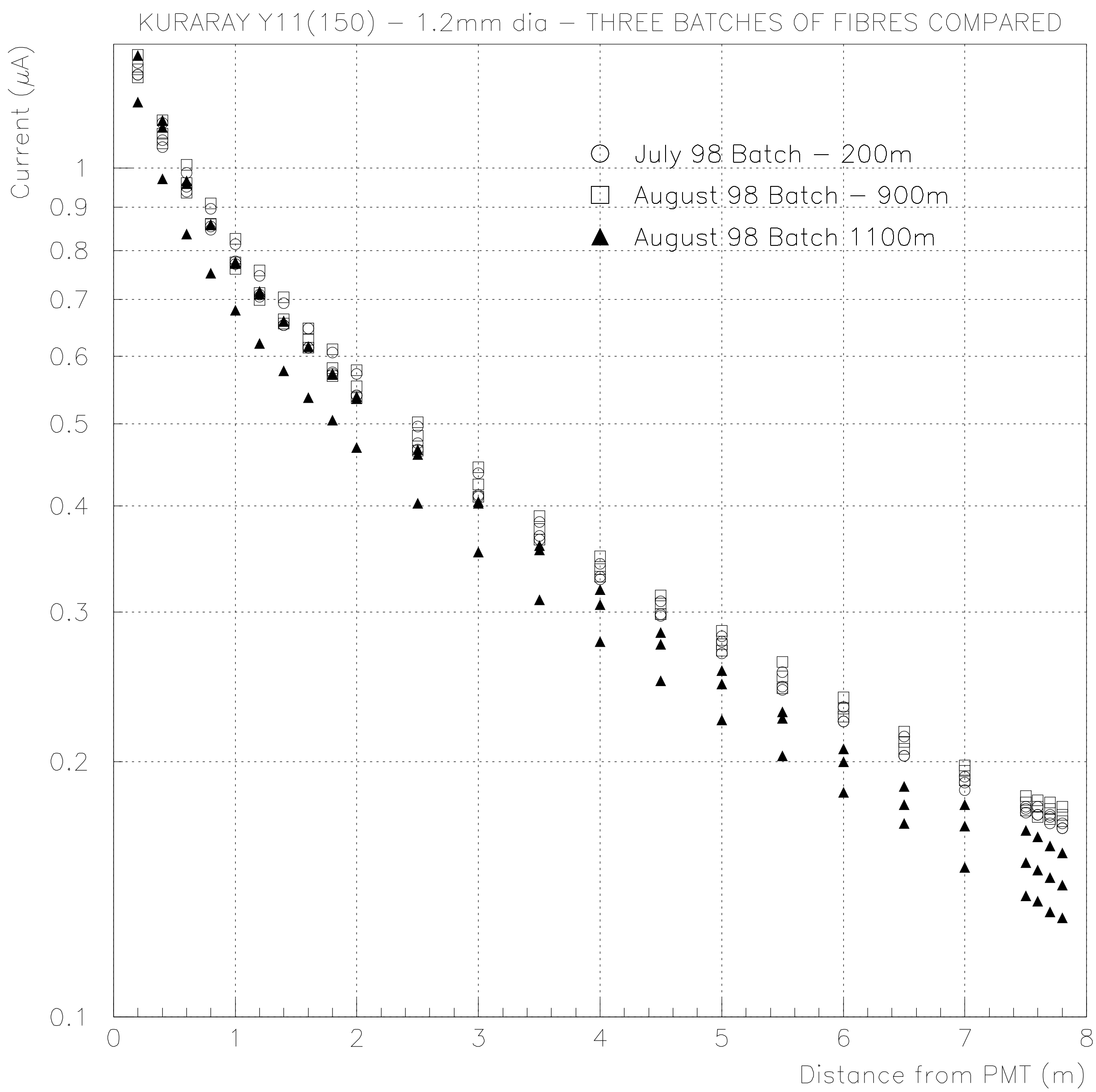

Figure 26: Inter and intra batch variation in light output for three different batches of Kuraray Y11(150), 1.2mm diameter fibre. The Y-axis has an arbitrary multiplicative factor of 10.

S.N	Spool	Production	Att. Length (cm)	Light Output (mV)
1	200m	22 July 98	No.1 - 490 No.2 - 455	No.1 - 4.25 No.2 - 4.14
2	900m	7 August 98	No.1 - 489 No.2 - 452	No.1 - 3.86 No.2 - 3.84
1	1100m	7 August98	No.1 - 421 No.2 - 411	No.1 - 4.37 No.2 - 4.00

Table 11: Kuraray's measurement of attenuation length and light output for three different batches of Kuraray Y11(150) 1.2mm diameter fibre. No.1 shows the measurement at the beginning of the spool and No.2 shows the measurement at the end of the spool. The details of measurement are discussed in text.

to get whatever extra light one can get. Figure 11 shows the light output from sept 97 first prototype module. That module was built using first batch of Bicron fibre, referred to as old Bicron fibre. The gain in light output, from that batch of Bicron fibre to 1.2mm Kuraray Y11(150) fibre is shown in figure 27. We see that just from fibre quality, compared to light output shown in figure 11, we should get atleast a factor of two light at the near end (about 2 meter from PMT) and a factor of 2.5 at the far end (between 7 and 8 meters from the PMT). The light output from the latest module built at Fermilab in early december gives about 5-6 photoelectrons at the near end and about 1.7 photoelectrons from the far end of the scintillator strip. The light increase from the first prototype module to the latest module, is more or less consistent within errors (on the lower side of the measurement), with the gain in light output due to better quality and larger diameter of the fibre used for the latest module. To further increase the light output from the modules, one has to work very carefully on several aspects of module building, like proper gluing of the fibres, very fine finish for the connectors to have optimum light transmission through the connectors, proper alignment of the WLS and the clear fibre and many such fine details. We also need to have scintillators with proper groove and proper TiO_2 coating. The last batch of scintillator unfortunately did not have uniform groove as shown and discussed earlier in the note. This could be one reason that the latest module did not give expected increase in light output from better quality and larger diameter fibre. Many more fine details need to be understood and parameters properly tuned for optimum light output.

1.3 Glue R&D

MINOS is one of the first experiments to use optical glue to put the fibre and scintillator together. None of the other major experiments, CDF, DØ and CMS have used glue for this purpose. Since the scintillator pieces used by these experiments are smaller and wider the fiber could be slid into the grooves. But for MINOS, the detector geometry requires that fibre be optically glued to the scintillator. Several hundred gallons of optical glue will be needed to put the whole detector together. Although the thickness of the glue between the fibre and the scintillator will be of the

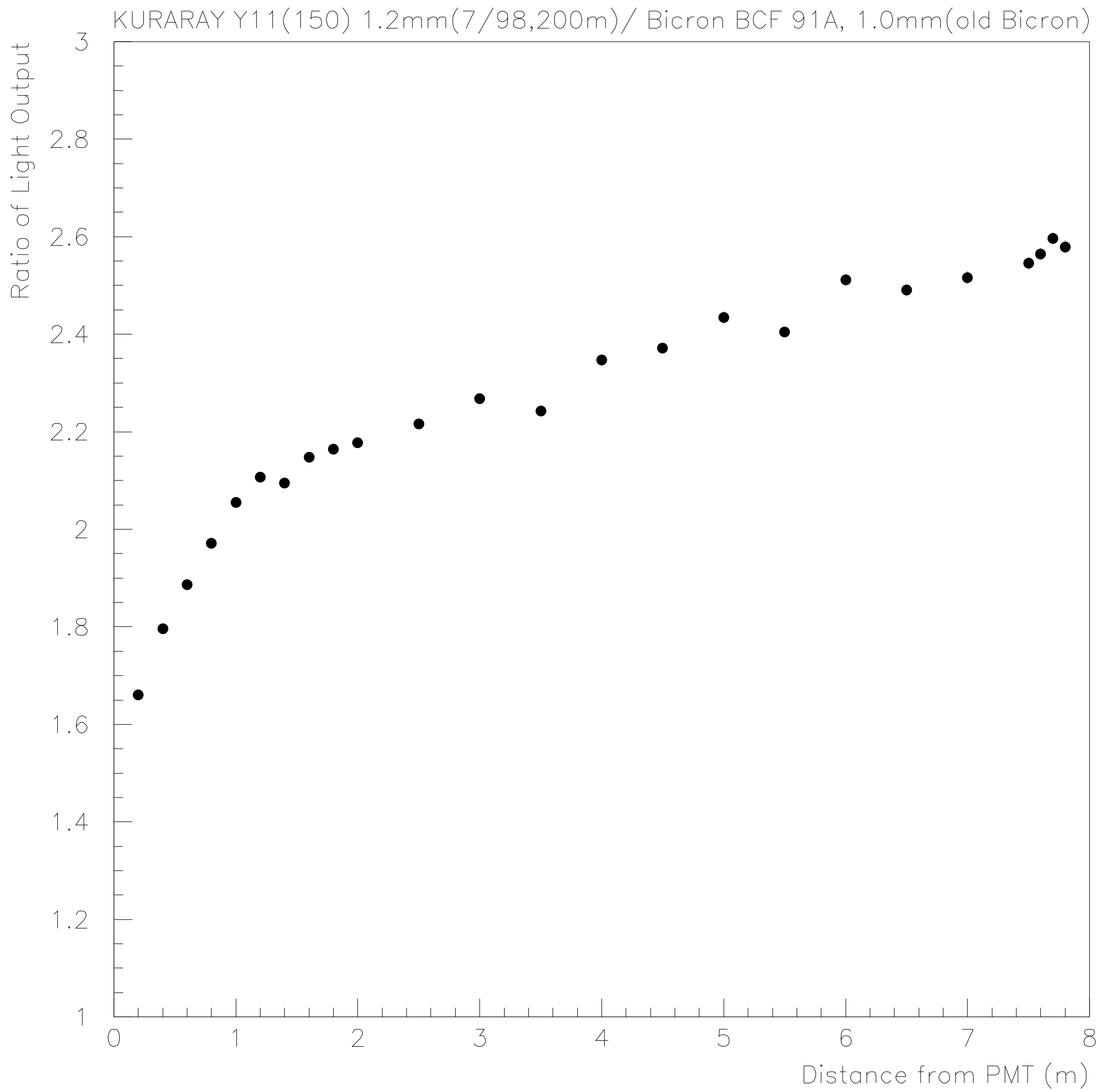

Figure 27: The expected gain in light output as a function of distance from the PMT, from the improved quality and increased diameter of the fibre, from first prototype module built at Fermilab in september 1997 with old Bicron fibre, 1.0mm diameter, and the latest module built at Fermilab in december 1998, using 1.2mm diameter Kuraray Y11(150) fibre.

Properties	Glue I	Glue II	Glue III
Resin	BC600	EPON 815	EPON 815
Hardner	BC600	TETA	B002
Ratio By Weight Resin:Hardner	100:28	100:13	100:50
Viscosity (cps)	800	500-700	1260
Cure Time Approx.(hrs)	24-48	24-48	24-48
Pot Life (minutes)	30	20	64
Specific Gravity	1.18	-	1.10
Index of Refraction	1.57	1.58	1.56
Peel Strength (lb/in)	1.69	1.18	1.45
Hardness Shore "D"	80	85	81
Overlap Shear (lb/sq. in.)	1163	1028	1322
Spectral Transmission	308-340nm > 90% 340-400nm > 95% >400nm > 98%	Better than BC600	Comparable to BC600
Effect of Ageng	Available	Available	Available
Estimated Price (USD) for complte MINOS detector	100K	20K	40K

Table 12: Properties of three different two component glues, BC600, EPON 815 + TETA, and EPON 815 + B002 selected for further studies.

order of few hundred microns, one would like to chose a glue with has very high transmission coefficient for green light. Since the detector life time will be atleast 10 years, one would also like that with time, the transmission through the optical surface does not change significantly. Other than these two factors, other major considerations are, viscosity, pot life, cure time, index of refraction and finally the price.

We have studied several UV curing, one component and non-UV curing, two component glues. Although the UV curing glues could be cured in few minutes under UV light and helps in handling a large amount of scintillator and fibre, it was found that UV curing glues are very expensive and extremely time consuming and labour intensive, to the extent that it is almost unrealistic to use it. Hence we settled down for two component glues, made of resin and hardner. We tested several of them for their properties and finally we selected only three for detailed studies. Table 12, shows the different chacteristics of these three, two component glues.

We see that these three glues are very comparable to each other in most of their properties. Although we have used BC600 from Bicron for most of our studies, based on light transmission properties, aging and the cost, we have selected EPON 815 + TETA for our detector construction. The last set of module at Fermilab was built using EPON 815 + TETA.

We have measured the transmission of light through these three glues. We find that the transmission through the glue for differeent wavelength light is almost identical, as shown in table 12. We have also looked at the aging properties of these glues. It has been found that EPON 815 + TETA ages very slowly, slower compared to Bicron BC600. Since the thickness of glue between the scintillator and fibre is of the order of few hundred microns, the aging of glue compared to aging of scintillator or fibre is almost negligible and hence more details, which has been shown at many collaboration meetings will not be discussed in this note.

1.4 Aging of Scintillators, Fibres and the Assembly

The normal expected life time for MINOS detector is estimated to be approximately ten years. It is a well known fact that scintillators and fibres developed with polystyrene do age. One must expect light loss as years go by. The detector elements are expected to slowly degrade and lose some of their efficiency over such a long period. We have tried to simulate and analyze the long term effects on different components of the active detector. The effort is to understand how much will be the light loss in the detector either due to degradation in scintillator, fibre or the completed assembly. The aim of this study is to estimate the aging of the detector in normal environment in the next ten years and build a detector which have sufficient light today and sufficient light ten years down the road, for the physics need of the time.

The accelerated aging test for the different elements of the detector (scintillator, fibre and glue) and their assembly is being done at high temperature (50^0C), cycled temperature (-30^0C to 50^0C, 3hrs at each temperature setting) and high humidity (50^0C and 95% humidity) in controlled environment. Since the detector modules will be transported from different collaborating institutions to Soudan mines in Minnesota and will have to be taken down in the elevator shaft, they might suffer some mechanical stress. We are also studying the effect of mechanical stress. All of these will be compared with aging that might happen at normal environmental condition or room environment.

We made 60cm long samples of Quick Plastic (QP), RDN 663 and RDN 262 scintillators. Samples of 8m long Bicron BCF 91-A, 1.0 mm diameter fibre have been made. We have also made complete assembly of 60cm long pieces of scintillators glued with 2.5m long Bicron fibres. Since the RDN's with a hole is not a practical concept, we have filled the holes in the RDN's and have made grooves on the side in which the fibre is glued. Two samples of each, the scintillator, fibre and the assembly is kept at room temperature (called controlled sample) and two samples of each goes into high temperature, cycled temperature and high humidity environment, respectively.

1.4.1 Aging of Scintillators

Table 13 shows the fractional light loss in different scintillators in these environments. We see that the controlled sample does not lose light. All measurements for the controlled sample are within measurement errors. High temperature, and cycled temperature where part of the cycle is at high temperature (50^0C) effects RDN sample much more than Quick Plastic in first two months. But in the next four to six months the RDN's lose less light compared to QP. Although high humidity environment is also at 50^0C, in the high humidity environment all the samples lose almost equal amount of light in first two months. But in the next four to six months the RDN's lose very small amount of light, may be another 3-5% while the QP loses almost 10% of light. We see that QP loses about 20% of light in 8 months of accelarated aging at high temperature which is almost being at normal temperature for nearly 10 years. The light losses in this sample confirms the general held view that most of the scintillators lose about 2% of light every year.

1.4.2 Aging under Mechnical Stress

We have also studied the effect of mechanical stress on the scintillators. 1.2 meter of scintillator pieces were put on an arc with radius of curvature 1.0m. Most of the RDN pieces broke. The QP pieces with 2.5m long bicron BCF-91A fibres, 1.0mm diameter glued to them were put on the arc for nearly two weeks. The samples were put on arc with grooves facing down and grooves facing up. Samples with grooves facing down showed no loss in light output, while the samples with groove facing up showed light loss of almost 50%. It seems that grooves got crazed while it was put on arc facing up. The samples with groove facing up were put on the arc for six more weeks. No further light loss was seen from the sample. The data suggests that a 1m arc is a very severe condition. Further studies for stress measurement with 1m arc was discontinued. Obviously MINOS detector will never be transported in such harsh conditions.

Further studies were done where two pieces of QP assembly, 1.2m long QP scintillator, with 2.5m long Bicron BCF-91A fibre, 1mm diameter, glued was put on an arc with radius of curvature of 2m. The groove was facing up. Light loss of 4-5% was observed in two weeks. Next measurement was taken after another 52 days. The measured light loss even after 66 days was about 5-6%, which could be very well within the systematics of the measurement. Thus no significant light loss was observed in the assembly on an arc of radius of curvature 2m in nearly 10 weeks.

1.4.3 Aging of Scintillator and Fibre Assemblies

Table 14 shows the fractional light loss in the complete assembly in these environments. We further see that in first two months the assembly with RDN samples lose more light than Quick Plastic in both high temperature and cycled temperature environment. For high humidity all the three samples lose much larger amount of light, compared to the light loss in high humid environment for the scintillator as shown in table 13. This suggests that high humid environment is effecting either the fibre or the glue. The controlled sample for QP does not show any light loss in 4 months, where as RDN 663 and RDN 262 shows light loss of 11% and 7% respectively. Unfortunately we have only one controlled sample of this scintillator and it is hard to say that 11% variation is fluctuation of some kind or light loss. If this is taken as light loss then we see that RDN 663 does not lose much light in any other environments. We also see that high humidity is effecting all the scintillator and fibre assembly much more than scintillators itself.

From the table 13 and 14 it is clear that the effect of aging was much more pronounced on RDN scintillators and related assemblies in first two months compared to QP. But QP has aged more in subsequent two months compared to RDN.

Data for 8 months of aging at high temperature for QP suggests that, in about 10 years of normal operation we would lose about 40% of light. But the scintillator only loses about 20% of light. It means that other 20% light loss comes from the fibre. It is possible that the fibre is open here. It is not covered by any glue and so it might have aged faster and added to this

Scintillators ($\rightarrow$)	Quick Plastic	RDN 663	RDN 262
Controlled Sample			
2 months	no loss	no loss	no loss
4 months	no loss	no loss	no loss
6 months	no loss	no loss	no loss
8 months	no loss	no loss	no loss
High Temperature			
2 months	4-10%	20-22%	18-21%
4 months	—	—	—
6 months	10-14%	24-26%	22-24%
8 months	17-19%	24-26%	22-14%
Cycled Temperature			
2 months	6-11%	18-21%	20-23%
4 months	—	—	—
6 months	8-11%	20-25%	25-27%
8 months	8-12%	19-25%	24-27%
High Humidity			
2 months	10-12%	6-8%	10-12%
4 months	—	—	—
6 months	14-18%	6-8%	10-12%
8 months	23-25%	8-10%	12-14%

Table 13: Fractional light loss in different scintillators after 2, 4, 6 and 8 months of accelerated aging in the given environment. The aging at high temperature (50^0C) for 2, 4, 6 and 8 months corresponds to respectively 2.7, 5.4, 8.0 and 10.7 yrs of aging at the normal room temperature ($\approx 72^0$F).

Scintillator Assembly (→)	Quick Plastic	RDN 663	RDN 262
Controlled Sample			
2 months	no loss	no loss	no loss
4 months	no loss	11%	7%
6 months	2-4%	18%	13%
8 months	2-4%	18%	13%
High Temperature			
2 months	12-16%	15-25%	24-34%
4 months	24-32%	25-34%	34-42%
6 months	32-35%	33-39%	40-48%
8 months	37-40%	38-42%	44-52%
Cycled Temperature			
2 months	14-18%	14-16%	14-18%
4 months	16-20%	24-26%	25-28%
6 months	16-21%	34-37%	34-36%
8 months	18-24%	38-42%	40-42%
High Humidity			
2 months	24-28%	25-27%	34-38%
4 months	36-40%	32-41%	43-45%
6 months	44-47%	37-46%	49-51%
8 months	50-53%	45-51%	53-55%

Table 14: Fractional light loss in different scintillator, fibre assembly after 2, 4, 6 and 8 months of accelerated aging in the given environment. The aging at high temperature (50^0C) for 2, 4, 6 and 8 months corresponds to respectively 2.7, 5.4, 8.0 and 10.7 years of aging at the normal room temperature ($\approx 72^0$F).

increased light loss. The light loss at high humidity is even higher which suggests that high temperature coupled with higher humidity is even more damaging to the system.

The thickness of the glue between the scintillator and the fibre is several hundred microns. Although there is some light loss in the glue due to high humidity, it is of the order of a percent or two which is within the systematic error of the measurement. Definitely the effect of the humidity on glue does not affect the light transmission in the assembly.

1.4.4 Light Loss in Bicron BCF-91A Fibre due to Aging

Further we have analyzed the data for aging of the fibres. We do not see any appreciable light loss in the controlled sample of fibre in 8 months at room temperature. The fractional light loss for different environment averaged over the fibre length is given in table 15. For high humidity case we have separated the data for two fibre samples. We see that the fibre loses less light from the near end compared to the far end and there is a definite slope in the data. It suggests that the humidity affects fiber such that light transmission decreases as the travelled length for light

Fiber	2 months $\approx$ 2.7 yrs	4 months $\approx$ 5.3 yrs	6 months $\approx$ 8.0 yrs	8 months $\approx$ 10.7 yrs
Controlled Sample	no loss	no loss	2-4% loss	2-4% loss
High Temperature (50^0C)	12-16%	24-27%	24-32%	28-35%
Cycled Temperature (-30^0C to $+50^0$C)	12-14%	22-25%	27-30%	34-36%
High Humidity 50^0C and 95% Humidity	NE -FE -	NE-FE -	NE-FE -	NE-FE -
fiber 1	10-22%	19-29%	21-29%	25-32%
fiber 2	2-11%	15-23%	19-25%	25-32%

Table 15: Fractional light loss in Bicron BCF-91A fibre, 1.0mm diameter, after 2, 4, 6 and 8 months of accelerated aging in the respective environment. Approximate years of aging at normal temperature, pressure and humidity is also given.

increases. This means that the attenuation length of the fibre decreases in high humidity.

1.4.5 Light Loss in Kuraray Y11(150) due to Aging

We have also aged Kuraray Y11(150), 1.0mm diameter fibre in all the three environments discussed above. Three fibre samples were kept at normal controlled environment. Two fibre samples each were placed in high temperature, cycled temparature and high humidity environment. Light output was measured after 83 days and 145 days which at high temperature is respectively equivalent to 3.5 years and 6.4 years at normal temperature. No light loss was observed within measurement errors either at high temperature, cycled temperature and high humidity.

This result is very different compared to aging result of Bicron BCF-91A fibre. The estimated light loss in Bicron fibre in the same time span was about 25%. Further studies are continuing to understand the discrepency between the results on two WLS fibres.

1.4.6 Effect of Bend on the Fibre

We have also studied the effect of bend on WLS fibres. It is expected that the fibres will be bend while they are introduced from the scintillator to the connector and then to the multiplexing box. The light output was measured with 11m long WLS Bicron fibre with and without bend. The bend radius was about 10cm. The fibre was bent at a distance of about 3m from the PMT. No apparent light loss was seen with a bend of 10cm. The measurements were made with few of the fibres and the results were repeated. No light loss was observed for any of the measurements. The bend radius is expected to be larger than 10cm and should not be a problem for MINOS.

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References

[1] Part of the text on “Two Step Process” is from an e-mail exchange between Richard Talaga of ANL and Brajesh Choudhary of Caltech.

[2] For details on dark box prepared at Caltech, please see NuMI-L-307.

[3] E-mail exchange between Brajesh Choudhary of Caltech and Osamu Shinji of Kuraray Incorporated of Japan.

[4] E-mail exchange between Brajesh Choudhary of Caltech and Kazuki Yagura of Kuraray Incorporated of Japan.

[5] E-mail exchange between Brajesh Choudhary of Caltech and Ken Heller of University of Minnesota.